Differential scattering of He\textsuperscript{2+} from He

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Abstract. Absolute cross sections, differential in angle and energy of the scattered particles, are obtained for single charge transfer and elastic scattering of He\textsuperscript{2+} from He for incident ion energies 200 eV to 600 eV and lab angles 2.5\degree to 20\degree. No ground state He\textsuperscript{+} are found and oscillations due to double charge transfer are observed in the elastic channel. These data are interpreted in terms of \textsuperscript{1}\Sigma\textsubscript{g} and \textsuperscript{3}\Sigma\textsubscript{u} potentials in the incident channel and curve crossings of this \textsuperscript{1}\Sigma\textsubscript{g} potential with higher states.

1. Introduction

The differential scattering of the simple ions H\textsuperscript{+}, He\textsuperscript{+} with the neutral atoms H, He has been the subject of extensive investigation, both theoretically and experimentally. These investigations have provided a good deal of information about the nature of these collisions. However, much less work has been done on another simple, yet important, system, He\textsuperscript{2+} + He. Most of the previous experiments on this system have been concerned either with only one of the many competing processes that can arise from a collision, often without energy analysis, or with angular distribution without regard to charge and/or energy state of the collision products.

It has long been recognized that single-electron capture is an important and sometimes dominant process in a multiply charged ion-atom collision. This process is characterized by the Coulombic repulsive force between the product ions. According to the well known Landau–Zener–Stueckelberg (LZS) theory (Landau 1932, Zener 1932, Stueckelberg 1932), the electron transition between two atomic systems in a slow collision often occurs as a result of the pseudo-crossing of the adiabatic potential energy curves of the quasimolecule formed by the colliding particles. For these systems the calculation of the transition probability is greatly simplified if the reaction is slightly exothermic so that the crossing occurs at sufficiently large internuclear separations where the asymptotic potential curves may be used. For years, the experimental results of single-electron capture by multiply charged ions have been used to test the validity of the LZS theory or its improved forms (Hasted \textit{et al} 1972). In the He\textsuperscript{2+} + He collision at low velocities, the principal mechanism for single charge transfer again appears to be curve crossing, but at much smaller internuclear separations where the molecular orbital approximation is valid and endothermic transitions predominate.

In this paper, we report the results of absolute differential measurements on the system He\textsuperscript{2+} + He in the energy range 200–600 eV (laboratory values for energy and

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Figure 1. Schematic of apparatus. Ions are extracted from the source and transported at an energy equal to $eV_0$, until they see the grounded disc; thereafter the beam energy is $eV_{ion}$. Following each set of deflection plates is an Einzel lens of circular apertures employed to increase the beam intensity. A ion source, B pre-analysis focus and steering, C mass analysis, D post-analysis focus and steering (and acceleration or deceleration). E Baratron, F target chamber, G scattering cell, H pivot, I energy analyser, J detector (channeltron).

beam. The inner cylinder containing a 1.0 mm x 5.4 mm exit slit is 47.8 mm in inside diameter and is mounted on a rotatable table pivoted about the centre of the cylinder.

The two cylinders are electrically insulated from one another so that the inner one can be used to collect the incident beam. Also mounted on the table are the energy analyser and the detector. The scattering angle is read out on a digital voltmeter which monitors the output of a high resolution potentiometer.

The 127° cylindrical electrostatic analyser, with a mean radius of 10 cm, has an entrance slit of 0.5 mm wide and 3 mm high, and an identical exit slit. The entrance slit, which is also the second defining slit of the scattered ions, is 35.56 mm from the exit slit of the scattering cell. With this geometry, the theoretical energy resolution (fWHM) is 0.5%, as compared to a measured value of 0.6 ± 0.1%, for the primary or elastically scattered beam. The slight difference is attributable partly to the energy spread associated with the ion source, and partly to the angular spread in the beam, as well as any imperfection in the alignment of analyser slits. Equal and opposite potentials are applied to the plates to deflect ions having the appropriate energy through an approximately circular arc. An analyser constant of 5.00 is chosen for this analyser, ie the voltage $V$ applied across the plates is related to the energy $E$ of the transmitted ions by

\[ E/q = 5.00 \ V \]

where $q$ is the ionic charge. It is obvious that, to pass through the analyser, singly charged ions require a voltage twice as high as the doubly charged ions having the same energy. It is this property that enables us to separate the charge-exchanged He$^+$ from the elastically scattered He$^{2+}$, both having nearly equal energies.

The Bendix 4013 CEM is operated with its input end at high negative potential while the anode end is grounded. Therefore the energy-analysed ions are accelerated to 2–3 keV or higher when they strike the CEM input end. The CEM is very well shielded from background count sources, including positive ion feedback.

The target gas pressure in the scattering cell is measured by an MKS Baratron (series 90) differential capacitance manometer. The unit was factory calibrated with a
2.2. Measurement procedure

To calculate the differential cross section from our experimental data, the following expression is used (Jordan and Brode 1933, Kaminker and Fedorenko 1955)

\[
\sigma(\theta) = \frac{N(\theta)}{N_0 n \int_{\lambda x} \omega \, dx}
\]

with

\[
\int_{\lambda x} \omega \, dx = \frac{abh}{d(2d + l + s) \sin \theta}
\]

(1)

where \( N_0 \) is the incident particle flux, \( N(\theta) \) the particle flux scattered into the detection solid angle at angle \( \theta \), \( n \) the number density of target gas, \( \int_{\lambda x} \omega \, dx \) an integral over the scattering volume, \( a \) the width of the scattering cell exit slit, \( b \) and \( h \) are the width and height of analyser slits, \( d \) the distance between scattering cell exit slit and analyser entrance slit, \( l \) the distance from scattering centre to exit slit, and finally \( s \) is the arc length along the mean circle between the two analyser slits. For our apparatus, equation (1) can be written as

\[
\sigma(\theta) = \frac{2e N(\theta)}{I_0 n \int_{\lambda x} \omega \, dx}
\]

with

\[
\int_{\lambda x} \omega \, dx = 1.33 \times 10^{-5} \sin \theta
\]

(2)

where \( I_0 \) is the incident He\(^{2+} \) current and \( e \) is the electron charge.

The general procedure for taking a measurement is as follows. At the beginning of each run, the incident beam direction was determined first. The incident beam was said to pass through the scattering centre when the minimum of cell current and the maximum of plate current occurred at the same angle. Figure 3 shows a typical current against angle plot of an aligned incident beam. This 0° reference was further checked by measuring scattered ion current at both positive and negative angles. Generally, the two angles differed by less than 0.2° in the 3°–4° region in order to have equal scattering intensities. The construction of the cell is equivalent to that of a Faraday cage, so it therefore serves as an excellent current collecting device without the need of suppressing secondary electrons.

With the table set at 0°, the beam energy was determined by the energy analyser. The table then was rotated to a desired angle \( \theta \) and the analyser potential was tuned for the inelastically, elastically, and charge-exchanged scattered ions to be transmitted. The \( \text{Cem} \) was first used as a current amplifier; its output current as a function of analyser potential was either recorded directly on an x–y recorder, or, at larger angles, integrated for periods of 15–30 s, as appropriate for the signal level. Then the counting circuitry was connected to the \( \text{Cem} \) and with the analyser potential set on each individual peak, the output pulses were counted for periods of 100 s. The background count rate, with the target gas shut off, was less than 0.3 counts s\(^{-1} \) which was small compared to normal count rates.

All of our measurements were taken with a gas pressure well within the linear region of a scattering signal against target gas pressure plot, usually below 10\(^{-3} \) Torr. In covering the angular range of our measurements, it was necessary to use two or three
Figure 3. Profile and alignment of incident beam. Curves are recorded by repeatedly rotating the scattering cell. As the exit slit of the cell aligns with the incident beam, the current collected by the cell drops. Part of the emerging beam enters the energy analyser. Curve A, energy analyser (EA) entrance slit current; curve B, scattering cell current; curve C, EA plate current.

different pressures because of the rapid decrease of scattering signals with increasing angle. A separate experiment was carried out to determine the absolute efficiency of our detection system on a He$^{2+}$ beam. The results indicated that at least 90% of the scattered ions were detected. As there was no noticeable difference in the pulse height spectra for the detection of He$^+$ and He$^{2+}$ during the entire experiment, we assumed that the efficiencies were the same for both ions even though the latter had almost twice as much energy as the former when striking the CEM funnel. This assumption as well as the detection efficiency are further supported by the findings of Burrous et al (1967).

In order to check our overall ability to make absolute cross section measurements, we scattered He$^+$ on argon at 400 eV and compared the elastic scattering results with those of Aberth and Lorents (1966) (figure 4). The agreement in both the curve slope and the magnitude of the cross sections is good, noting that in their large angle data the inelastic contribution due to insufficient analyser resolution was considerable.

3. Results and discussions

3.1. Energy analysis and exit channel identification

A typical energy spectrum of the scattered ions at $\theta = 5^\circ$ for $E = 600$ eV is shown in figure 5. The abscissa is energy per unit charge, $E/q$, or equivalently, five times the energy analyser voltage $V$ since $E/q = 5-00$ V. At this incident energy and angle, three peaks are observed:

(i) A peak A corresponding to the elastically scattered He$^{2+}$ for which the energy is $E_e = E \cos \theta^2$.

(ii) Two peaks B and C appearing at approximately twice the analyser voltage for which the elastically scattered He$^{2+}$ (peak A) is seen. Therefore, as explained in the last
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Figure 4. Elastic scattering of $\text{He}^+ + \text{Ar}$ at 400 eV; ○ present data; - Aberth and Lorentz (1966).

Figure 5. Representative energy spectrum of the scattered beam. Peak A is the elastically scattered $\text{He}^{2+}$, peaks B and C are $\text{He}^+$ due to single-electron capture. Two of the excited levels of He are also indicated. $E = 600$ eV, $\theta = 5^\circ$.

section, these two peaks are due to $\text{He}^+$ arising from the process of single-electron capture,

$$\text{He}^2+ + \text{He}(1s^2) \rightarrow \text{He}^+(1s) + \text{He}^+(nl) + Q.$$  

Peak C is related to the exit channel $\text{He}^+(1s) + \text{He}^+(n = 2)$ with $Q = -11.02$ eV, and peak B is produced by scattering corresponding to the channels $\text{He}^+(1s) + \text{He}^+(n = 3, 4)$ with $Q = -18.55$ and $-21.19$ eV, respectively.

In the same figure, locations of some excited levels of He are also indicated even though no scattering leading to their excitation is observed. For incident energies below
500 eV, the excitation scattering remains unobservable through most of the angular range except at the largest angles where its cross sections are approximately two orders of magnitude below the elastic cross sections. At 600 eV, a broad excitation peak (almost three times as broad as the elastic peak) with $Q \approx -30$ eV begins to show up at $\theta = 8^\circ$ and reaches its maximum at $\theta = 11^\circ$ where its height is about one-tenth of the elastic peak.

The strong, and quite interesting, energy and angular dependence of the single-electron capture exit channels is clearly demonstrated by the exit channel spectra shown in figure 6. The ordinate is the He$^+$ counting rate arbitrarily normalized to the highest peak at the largest angle for each energy, and the abscissa is the energy defect $Q$ with the observed channels indicated. At our energy resolution of $0.6 \pm 0.1 \%$, the following points are pertinent: (i) the He$^+$ fine structure levels are effectively degenerate; (ii) He$^+(n = 2)$ can be separated from the He$^+$ ground state and He$^+(n = 3)$, but for $n \geq 3$ all $n$ levels are blended. The opening of a channel varies with increasing incident energy and scattering angle: at a larger incident energy any given channel opens at a smaller angle, and at a given angle more excited states are opened for higher incident energy. This latter feature is most clearly illustrated by figure 7, where at $\theta = 9^\circ$ the exit channel spectra for different incident energies are shown. For any incident energy, the channel that first opens and remains significant throughout the whole angular range is He$^+ +$ He$^+(n = 2)$ which is endothermic by 11.0 eV. Other channels possessing higher endothermicity open at larger angles; as the angle increases further, the exit

![Figure 6](image-url)  
**Figure 6.** Representative data showing exit channel spectra of single-electron capture. The cross hatching denotes closely spaced channels. Curves show data after smoothing and averaging. (a) 300 eV, (b) 600 eV.
channels include higher and higher excited states of He\(^+\) and finally proceed smoothly into the continuum. The competition among the various channels in the unresolved groups as the scattering angle increases is evident from these spectra. It is worth noting that in all of these measurements the highly exothermic ground state channel He\(^+(1s) + He\(^+(1s)\) (\(Q = 29.82\) eV), which is the only exothermic channel for the He\(^2+\) + He system, has cross sections below the \(10^{-20}\) cm\(^2\) detection limit of our apparatus and hence cannot be seen on the exit channel spectra.

To our knowledge, five He\(^2+\) curves have been calculated to date: He\(^2+\) + He\(^+(1s)\) \(\rightarrow\) \(\Sigma_x^+\) (Brown 1965, Ellison and Wu 1967), He\(^+(1s) + He\(^+(1s)\) \(\rightarrow\) \(\Sigma_x^+\) and \(\Sigma_u^+\) (Kolos and Rootham 1961), and He\(^+(1s) + He\(^+(2s)\) \(\rightarrow\) \(3\Sigma_u^+\) (Brown 1965). The most accurate calculations, those of Brown (1965), are carried out down to internuclear separation of \(2a_0\) for the initial states of the collision, while the electron capture in our experiment occurs at separations of the order of \(1a_0\) or less (discussed in the following section). Thus, no useful discussion of the transition in terms of these calculated molecular curves can be made, but they do indicate that the \(g, u\) splitting may be significant at somewhat smaller internuclear separations. Ellison and Wu (1967) apply an atoms in molecule calculation to the ground \(\Sigma_u^+\) state and the \(\Sigma_x^+\) and \(\Sigma_u^+\) states down to \(1a_0\).

3.2. Differential scattering cross sections

The cross sections obtained from our measurements for elastic scattering and single-electron capture are shown in figures 8 and 9 in terms of the reduced coordinates \(\rho = \theta \sin \theta \sigma(\theta)\) and \(\tau = E \theta\), where \(\theta\) is the scattering angle, \(E\) the incident energy in eV, and \(\sigma(\theta)\) is the differential scattering cross sections (all in the laboratory frame). As can
Figure 8. Differential elastic scattering cross sections at 200 eV: ○ present data; ······ calculations using $V(R) = (4/R)\exp(-R/a)$.

Figure 9. Differential elastic scattering and single-electron capture cross sections at (a) 400, (b) 300, (c) 600, (d) 500 eV: ○ elastic; ······ capture into $n = 2$ state; △ capture into $n = 3$ and higher states; ······ total; ······ calculations using $V(R) = (4/R)\exp(-R/a)$.

be seen in the exit channel spectra, the peaks are broadened as angle increases. This is caused by an energy spread of kinematic origin in the scattered ions associated with the finite angular resolution of the detection system, which is roughly

$$\Delta E = 2E\theta\Delta\theta.$$

As a result, the count rate obtained when the analyser voltage is set on a peak centre is
actually less than the ion flux scattered into the analyser. This peak broadening effect has been taken into account in calculating the absolute value of the differential cross sections, the correction being accurate to about ±20%.

Also shown in the figures are two differential cross section curves calculated from the exponentially screened Coulomb potential \( V(R) = (z_1 z_2 / R) \exp(-R/a) \), where the \( z \) are nuclear charges and \( a \) is the electron screening length in atomic units. For the upper curve, the screening length used is that given by Bohr, and for the lower curve we use the value which Carlston (1971) has chosen to fit his H+–He data. The latter choice is permissible since the incident particles in both cases are totally ionized. A theoretical calculation from such a potential describing the interaction between two colliding systems should give approximately the total differential cross section—total in the sense that it accounts for all particles scattered into some angle \( \theta \), elastically and inelastically. Using an estimate for resonant double charge transfer (discussed below) based on the elastic cross sections we show in the figures an experimental \( \rho \), the sum of all processes, which is in reasonable agreement with the \( \rho \) predicted by the screened Coulomb potentials.

As in the He\(^{2+} \) + He scattering observed by Lam et al (1973), our experimental curves for elastic scattering display oscillatory structures characteristic of resonant charge exchange for symmetrical systems; in this system, double charge exchange. This electron exchange oscillation arises from the interference between the gerade, \((1^2 \Sigma_g)^+\), and ungerade, \((1^2 \Pi_u)^-\), potential curves of the incoming system He\(^{2+} \) + He. Two features of the oscillation are evident: (i) the observed amplitude of oscillation increases as incident energy decreases; and (ii) the envelopes of the oscillation are slowly varying for small \( \tau \) but drop off rapidly at \( \tau \approx 400 \text{ eV deg} \). The damping of the oscillations with increase in energy comes about from the angular averaging and the fact that the oscillations are more closely spaced in angle with increasing energy. The drop-off, as we will see below, is due to the onset of the process of single-electron capture which removes ions otherwise available to the inelastic channel and thereby causes a reduction in the elastic scattering intensity.

In a previous study of He\(^{2+} \) + He, Latypov et al (1970) measured the total cross section for the production of slow He\(^{2+} \) ions. As their apparatus did not discriminate ionization from charge exchange, their measured cross section is the sum of double ionization, resonant charge exchange, and single-electron capture with target ionization. Since our measurements indicate that double ionization is negligibly small and single-electron capture into the continuum of He\(^+ \) is significant only at larger angles, we may take it that their value of \( 3.5 \times 10^{-16} \text{ cm}^2 \) at 400 eV is attributable mainly to the process of resonant charge exchange. This fairly large total cross section seems to further support the conclusion that the observed oscillatory structure is due to the resonant double-electron capture. Contrary to this conclusion, Lichten (1965) estimated that, in our energy region (\( v < 0.1 \text{ au} \)), no oscillatory resonant charge exchange for the system He\(^{2+} \) + He would be expected. The prediction was made based on adiabatic correlations of molecular states. However, it seems that the collision should be described by a quasi-adiabatic correlation in which the gerade state derived from He\(^{2+} \) + He is best treated as going to the united-atom state \((2p)^2\) of Be\(^{2+} \) as Lichten proposed for higher energy collisions and therefore separates significantly in energy from the corresponding ungerade state and is crossed by a number of states of the same symmetry (see figure 10).

It is further noted at small \( \tau \) the spacing in \( \tau \) of the oscillations for double charge transfer at these energies appear to be almost twice the spacings for single charge transfer in He\(^+ \) + He (Smith et al 1965). This is consistent with the fact that exchange interaction
for double charge transfer at large $R$ has an exponential screening approximately twice that of single charge transfer (Komarov and Yanev 1967). At small $R$ the states involved for these systems differ only in that the $n_{ij}^+$ has an extra electron in a molecular orbital which is not involved in the charge transfer process.

The elastic curves can be used to estimate potentials via the semiclassical method for the $(\Sigma_u^+)^*$ and $\Sigma_u^+$ states leading to $\text{He}^{2+} + \text{He}$. In this method the centre of mass, elastic scattering cross section is written (Smith 1964a, b)

$$\sigma_e(\theta) \simeq \frac{1}{2} \left[ \sigma_g(\theta) + \sigma_u(\theta) + 2\sigma_g(\theta)\sigma_u(\theta) \cos[(A_g - A_u)/\hbar] \right]$$

where $\sigma_g(\theta)$ and $\sigma_u(\theta)$ are the classical elastic scattering cross sections of the gerade and ungerade potentials respectively and $A_g$ and $A_u$ are the corresponding classical actions (Olson and Smith 1971), where the contributions from angles $(\pi - \theta)$ due to the nuclear symmetry have not been included as they are small for our values of energies and $\tau$. Lam et al have used such a formula to obtain an estimate of these two potentials based on their elastic scattering data. They required that their chosen potentials, which were Morse potentials, reproduce the experimental oscillations in the cross section and, as they did not have absolute cross sections, they constrained the potential to match Brown's (1965) calculated potentials at $R = 2.5\ a_0$. We added a small repulsive term,
4 \exp(-5R)/R$, to change the spacing somewhat at larger $\tau$ and as can be seen in figure 11 these potentials result in cross sections which reproduce the oscillatory structure in our experiments over the full energy and angular range. In these calculations approximate angular averaging is included for comparison with the data. The calculated cross sections appear to be somewhat larger than our absolute cross sections and have a different slope at small $\tau$ prior to the onset of the inelastic single charge transfer channel.

![Figure 11](image)

**Figure 11.** Elastic scattering cross sections at three energies: --- experiment; ----, based on potentials obtained from oscillations normalized to the average of the measured cross sections at small $\tau$; ----, based on potentials normalized to calculation of Brown (1965) at large $R$. (a) 200 eV, (b) 400 eV, (c) 600 eV.

For these reasons we estimated a new pair of potentials which also reproduced the oscillations but which were required to agree in absolute value with the average of the experimental elastic cross sections for all the energies measured here at small $\tau$. As the oscillations were equally spaced for a broad range of $\tau$ we chose simple exponentials with equal exponents. The exponents were assigned the value of 3 au to roughly reproduce the average slope of the elastic cross sections at small $\tau$ and a small screened Coulomb repulsive part was added to force agreement with the oscillatory structure observed at large $\tau$ (see figure 11). No attempt was made to make these curves reproduce the results of Lam et al at lower $\tau$ than are shown here. However, the two sets of data do overlap. The present quasi-molecular potentials associated with the incident channel are, in atomic units,

$$V_s(2p\sigma, 2p\sigma) = 23 e^{-3R} + \frac{4 e^{-9R}}{R}$$
and

$$V_u(1\sigma, 2\sigma) = 6.8 e^{-3R} + \frac{4 e^{-9R}}{R}.$$  

The above potentials apply in the regions, $0.7a_0 < R < 1.7a_0$ for $V_u$ and $0.5a_0 < R < 1.3a_0$ for $V_v$. However, they can only be verified by experiment at low $\tau$ prior to the inelastic drop, i.e. the first curve crossing of the gerade potentials. The potentials are extremely sensitive to the value of the absolute cross sections as can be seen in figure 12 where we compare the above gerade potential to theoretical estimates and to that of Lam et al as modified, which was normalized to theory. Because the uncertainties in the measured absolute cross sections are large the uncertainties in the potential function are also large. This emphasizes the need for additional measurements of absolute cross sections or accurate $ab\ ini\ initio$ calculations at smaller values of $R$.

![Figure 12](image)

**Figure 12.** Excited $^1\Sigma_g^+$ potentials of He$^+$. Ellison and Wu (1967) approximation 1. , semi-empirical potential normalized to Brown (1965) calculation at $R = 2.5$ au (Lam et al 1973). , semi-empirical potentials normalized to measured absolute cross sections.: Brown (1965) calculation: $\bigcirc$ crossing points.

Two widely spaced perturbations appear clearly on the 200 eV data (Smith et al 1965). Structure can also be seen on the 300 and 400 eV data prior to the drop in the cross section, although not as clearly. We interpret these as due to the curve crossing of the gerade states of the same symmetry leading to single charge transfer in the $n = 2$ state of He$^+$ (see figure 12). Using the $(^1\Sigma_g^+)$ potential based on the measured absolute cross sections, the crossing occurs at $0.94 \ a_0$, whereas for the potential fixed by theory, that of Lam et al as modified here, the crossing point would be at $1.17 \ a_0$. The crossings of the higher $^1\Sigma_g^+$ states indicated in figure 12 are not evident in the elastic scattering cross sections.

For each energy, two experimental curves are shown for the process of single-electron capture (figures 9–11). The one labeled $\rho_2$ corresponds to the $n = 2$ channel and
the other, labeled $\rho_3$, corresponds to the unresolved group of $n = 3$ and all other higher states. Two distinct features can be seen on these curves. First, the cross sections are negligible for small $\tau$ values and then rise up sharply to their first maxima; $\rho_2$ rises to its first maximum at $\tau \approx 2800$ eV deg and $\rho_3$ at $\tau \approx 4000$ eV deg. Second, following the first maxima the curves oscillate while dying down. These general features are common to inelastic scattering via curve crossings as observed for instance in the inelastic differential scattering of the system He$^+ +$ He by Lorents et al (1966). According to the LZS approximation, the oscillations arise as a result of interference between the two scattering amplitudes associated with the inbound and outbound trajectories. For scattering to an angle with distance of closest approach larger than $R_x$, the internuclear distance corresponding to the pseudo-crossing point of the non-adiabatic potential energy curves, few transitions can be expected to take place. Since the outgoing channels observed in this experiment are all endothermic, the crossings can occur only at small internuclear distances. Based on the screened Coulomb potential

$$V(R) = \left(\frac{4}{R}\right) \exp\left(-\frac{R}{0.56}\right),$$

the observed transitions are estimated to take place in regions of about 1.07--0.85 au for the $n = 2$ channel which is in reasonable agreement with earlier estimates and about 0.93--0.7 au for the higher states channels. Here it should be pointed out that since the interaction potentials are in fact different for the elastic scattering and for the single-electron capture, one impact parameter will not be related to the same $\tau$ in both cases and therefore this explains why the electron capture curves are seen to rise to their maxima before the elastic curves drop off rapidly. Because the outgoing potential in the single charge transfer state is considerably weaker than that of the incoming channel the differences in onset in the two cases is almost a factor of two.

As there are two $^1\Sigma_g^+$ states leading to the He$^+ +$ He$^+$ ($n = 2$) exit channel, the $(1s\sigma, 2s\sigma)$ and $(1s\sigma, 3s\sigma)$ quasi-molecular states, (figure 12), the oscillations in $\rho_2$ cannot be simply interpreted. The second peak in the $\rho_2$ curves appears to be due to the first maxima for the crossing by $(1s\sigma, 3s\sigma)$ state. From the previous discussion we estimate this crossing to occur in the vicinity of 0.85 $a_0$ on the elastic potential based on absolute cross section and 1.05 $a_0$ on that normalized to theory. For the first of these crossings we have parametrized a simple different potential valid in the vicinity of the crossing between the incoming channel $^1\Sigma_g^+$ state and the outgoing $^1\Sigma_g^+$ state of the form,

$$V_q(1s\sigma, 2s\sigma) - V_q(2p\sigma^2) \approx (\Lambda + 1/R_0) \{1 - \exp[\alpha(R_x - R)]\},$$

where $R_0 = R$ for $R \geq R_x$ and $R_0 = R_x$ for $R < R_x$. $\Lambda$ is the energy defect at infinity, for the state in question 0.404 au, $R_0$ the crossing point and $\alpha$ a screening parameter. Using $R_0 = 0.94$ $a_0$, as determined from the elastic scattering curve, a screening constant $\alpha = 2.5$ gave, roughly, both the appropriate inelastic threshold in $\tau$ and the measured spacing of the perturbations on the elastic curves. Experimentally the half-maximum for the first crossing is close to 2400 eV deg for all energies. This potential is plotted in figure 12 along with the potentials for the elastic scattering data. The validity of the potentials rests heavily on the accuracy of the absolute cross sections in the elastic channel which was used to determine the $R_x$ and the incident channel $^1\Sigma_g^+$ curve. In figure 12 the crossing of the $(2p\sigma^2)$ and $(1s\sigma, 2s\sigma)$ states has a much less dramatic form than the corresponding crossing in He$^+ _2$ (Olson 1971) as the binding energy of the electron, $(1s\sigma)$, is changing rapidly in the region of the crossing and the He$^+_2$ potentials.
are scaled into smaller $R$. The screening parameter in the above equation essentially determines the difference in slope between the two potentials at $R_s$. Using this difference and the values of the first maxima in $\rho_3$, we estimate the coupling potential at $R_s$ between the two $^3\Sigma_g^+$ states to be $0.17 \pm 0.05$ au.

We have also integrated the differential cross sections over the angular range of the data at 600 eV to obtain the total cross section for single-electron capture. The value thus obtained is $2.0 \times 10^{-17}$ cm$^2$. The error due to neglecting the contribution from large-angle scatterings is estimated to be less than about 50%. This cross section can be compared with the results of Latypov et al (1970) who have also measured the total cross section for the production of slow singly charged ions in the He$^2+$ + He collisions. Their cross section, in addition to single-electron capture, contains contributions from single ionization. But as our measurements indicate, in our energy region, ionization is negligibly small and so we can take their total cross section as that for single-electron capture. At 600 eV, their value is about $3.5 \times 10^{-17}$ cm$^2$. Thus our total cross section is significantly lower than theirs but is about equal to the extrapolated value of the results of Hertel and Koski (1964).

We have presented absolute differential cross sections for elastic scattering and single charge transfer into excited states of He$^+$. Here the inelastic effects appear to be well described by curve crossing of a series of quasi-molecular states with the $(^3\Sigma_g^+)^0$ state associated with the incident channel and the principal oscillations in the elastic channel are a result of double-electron transfer. It is clear from our analysis that the qualitative features of the cross sections are easily described but that, in inverting the data to locate the curve crossings and determine the interaction potentials, the uncertainties in the absolute cross sections also produce large uncertainties in the results. Since this is a simple two-electron system of fundamental importance in a number of physical phenomena, we feel additional experiments and calculations are warranted.

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