Scattering of $\text{He}^{2+}$ from $\text{N}_2$; comparison of $\text{He}^{2+} + \text{N}_2$ with $\text{He}^{2+} + \text{Ne}$ and $\text{Ar}$

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Abstract. The scattering of $\text{He}^{2+}$ ions from molecular nitrogen has been studied in the angular range 0 to 20° and in the energy range 200 600 eV. Elastic, simple inelastic, and single-charge-transfer scattering were observed using energy analysis of the scattered He ion to distinguish among the different processes at each observed scattering angle. The data are presented in the form of exit-channel spectra and cross section against reduced scattering angle. For scattering without electron capture, a binary collision model (in which one of the two nitrogen nuclei exchanges momentum with the projectile, the other actin as a "spectator") is adequate up to a reduced scattering angle of approximately $\Theta = E\theta - 6000$ eV deg for describing the average elastic energy transfer. Evidence for spin-excitation rules in low energy ion-molecule collisions was observed. For $\text{He}^{2+} + \text{N}_2$ collisions the charge-transfer processes had the largest cross section throughout our range of energies and angles, particularly at the larger value of $\Theta$. The exit-channel spectra for $\text{N}_2$ targets are compared to those taken for $\text{Ne}$ and $\text{Ar}$ targets and strong similarities are noted. Charge-transfer processes leaving the outgoing $\text{He}^{+}$ in its ground state produced very high excitation of the targets (about 45 eV above the ground state for $\text{N}_2$), showing a preference for small values of $Q$, where $Q$ is the energy defect.

1. Introduction

Most experimental studies of ion-molecule collisions have emphasised singly charged ions. The experiments reported here deal with the differential scattering of doubly charged helium from molecular nitrogen, in the energy range 200 600 eV and angular range 0 to 20°, in the laboratory frame. This work is an extension of previous experiments performed in this laboratory involving rare gas atomic targets. We have specifically investigated the momentum-exchange mechanisms in ion-molecule collisions, as well as inelastic and charge-exchange scattering. Comparison is made between $\text{He}^{2+} + \text{N}_2$ spectra and $\text{He}^{2+} + \text{Ne}$ and $\text{Ar}$ spectra taken in this laboratory.

2. Apparatus

The apparatus used here has been previously described in the literature (Chen et al. 1975, Chen 1972). The only modification was the addition of improved digital detection electronics. The experiment essentially consists of directing a beam of

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monoenergetic He\(^{2+}\) ions into a scattering cell in which a gas of N\(_2\) molecules is contained at a known density, consistent with single collision conditions. Ions scattered at a given angle \(\theta\) are allowed to enter an electrostatic energy analyser. The transmission energy of the analyser is swept through a certain range of energies, and transmitted ions are detected and counted as a function of their energies and scattering angles. These data are then presented to a digital computer which calculates absolute scattering cross sections for various exit channels and produces plots of the data.

3. Cross section determination

Differential cross sections are calculated from our data using the expression

\[
\sigma_\xi(\theta) = N(\theta, \xi) \left( N_0 a \int_{\Delta x} \omega \, dx \right)^{-1}
\]

with

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

where \(N(\theta, \xi)\) is the flux of particles scattered at angle \(\theta\) and nominal energy \(\xi\), corrected for instrument broadening, \(N_0\) is the incident-particle flux, and \(a\) is the target gas density. The integral is of the detector solid angle integrated over the scattering volume (Jordan and Brode 1933, Kaminker and Fedorenko 1955), where \(a\) is the width of the scattering cell exit slit, \(b\) and \(h\) the width and height of the electrostatic analyser entrance slit, \(d\) the distance between these two slits, \(l\) the radius of the scattering cell, and \(s\) the mean arc length of the analyser. Equation (1) is valid for angles \(\theta\) large enough that the length \(\Delta x\) of the collision volume viewed by the detector is smaller than the diameter of the scattering cell, giving for our case \(\theta_{\text{min}} = 2.4^\circ\).

For our instrument,

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

Kuyatt and Rudd (1963) have shown that the flux of detected particles can be corrected for instrument broadening according to

\[
N(\theta, \xi) = S(\theta) D/w_2 \xi
\]

where \(S\) is an integral of the analyser output over the peak, and \(D\) and \(w_2\) are the dispersion and exit slit width of the analyser. Our analyser has a dispersion of 10 cm and a 0.5 mm wide exit slit, so the final expression for the cross section (in cm\(^2\)) is

\[
\sigma_\xi(\theta) = 3.01 \times 10^{-1} \frac{S(\theta) e \sin \theta}{\xi I_0 n}
\]

where \(e\) is the electronic charge and \(I_0\) is the beam current.

As an overall check on our cross section calibration we measured the differential cross section for the elastic scattering of He\(^+\) on Ar. Comparing with previous measurements performed with this apparatus, we found our measurements to be low by a factor of 2.0, believed to be due to reduced detection efficiency; hence, we included this factor in the calculation of the absolute cross sections.
4. Results

4.1. $\text{He}^{2+} + \text{N}_2$ scattering

Data for elastic and inelastic scattering are presented in figure 1 in the form of exit-channel spectra (ECS), or intensity against electronic energy change, $Q$. The data shown indicate two peaks labelled A and B. In an ion–atom collision peak A would correspond to an elastic scattering of the projectile. For an ion molecule collision there is in each encounter, an elastic or momentum-exchange collision with each of the nuclei in the molecule resulting not only in a deflection of the target molecule but in vibrational and rotational excitation. Peak A therefore corresponds to this total elastic energy transfer. The calculation of $Q$ requires an assumption regarding the specific momentum-exchange mechanism. There are two limiting cases for a target diatomic molecule. The first, known as the binary model, assumes that the projectile exchanges momentum with a single molecular nucleus, the other acting as a simple spectator during the interaction. The second, known as the rigid model, considers the atoms of the molecule to be rigidly bound to each other, hence the effective target mass is the entire molecular mass. We have used the binary model to generate the ECS shown in figure 1 for various reduced scattering angles $\tau (\tau = k0)$. Peak A for most ECS falls close to $Q = 0$, indicating that the binary model yields a reasonable

![Figure 1. Typical exit-channel spectra for elastic and inelastic He$^{2+} + \text{N}_2$ scattering.](image-url)
estimate of the total elastic energy transfer. However, at the largest value of \( \tau \) observed, peak A appears to have shifted to a slightly exothermic \( Q \), indicating that here the binary model assumes too small a value for the target mass. We thus conclude that for this system the binary model is at least valid up to \( \tau = 6000 \) eV deg. Fernandez et al. (1975) conclude that the binary model does not apply at equivalent \( \tau \) values for 1, 2 and 3 keV incident Ar\(^+\) on \( \text{N}_2 \). However, inspection of their 1 keV data indicates that the binary model appears to apply for this system below a \( \tau \) value of about 1500 eV deg.

Sato et al. (1976) find that for Li\(^+\) on \( \text{N}_2 \) in the angle and energy range 1–7° and 0.5–1 keV the elastic peak lies between the two limits discussed here. For 1 keV incident Li\(^+\) the position of the elastic peak could be estimated via a classical impulse approximation (Baudon 1973) in which it is assumed that the projectile makes a binary collision with each nucleus of the target. One would expect the simple binary model to apply best at large \( \tau \) where the energy transfers are large (here they are lower than the dissociation limit of \( \text{N}_2 \)) and the distances of closest approach small, and it should break down when the impact parameters are quite large (Sigmund 1976). Here there appears to be an intermediate region where the binary model gives a reasonable estimate of the average elastic energy transfer. It should be emphasised that at the lower incident ion energies the observed elastic peak widths are broader than the differences between the limiting energy transfers. Therefore the peak shape in addition to the experimental width has contributions from collisions with both target centres. Any ambiguity in \( Q \) resulting from an incorrect choice of \( Q = 0 \) does not, however, affect our subsequent discussion of the spectra.

Peak B is centred at about \( Q = -19 \) eV and in general has its onset at about \( Q = -13.5 \) eV. There are several exit channels that possibly contribute to this peak. The first possibility is the \( x \Sigma_b^+ \rightarrow b \Sigma_a^+ \) transition in \( \text{N}_2 \). Ionisation to any one of several states of \( \text{N}_2^+ \) with the concomitant release of a free electron comprise the remaining possibilities. Since the lowest state of \( \text{N}_2^+ \) is 15.6 eV above the ground state of \( \text{N}_2 \), we conclude that excitation to the \( b \) state certainly accounts for at least that portion of the peak \( Q > -15.6 \) eV. In the 200 eV ERS, unlike the 600 eV ERS, the left-hand tail of peak B is rather sharply decreasing, and terminates at about \(-25 \) eV, especially at the larger scattering angles. The different character of the tail of peak B between the 200 eV and 600 eV ERS may be interpreted in terms of competition between ionisation (without charge transfer) channels and charge-transfer channels. In the 200 eV case the slowly moving projectile is more likely to capture an ejected electron than for the 600 eV case. Our conclusion is that peak B in the 200 eV ERS is primarily due to excitation of the \( b \) \( \Sigma_a^+ \) state of \( \text{N}_2 \) over a range of vibrational states, while at 600 eV there is an additional contribution due to ionisation of \( \text{N}_2 \) to any of several states of \( \text{N}_2^+ \).

Selection of the \( x \rightarrow b \) transition by the He\(^2+\) + \( \text{N}_2 \) system has several interesting implications. The \( b \) state is Coulombic at internuclear separations \( R \sim 2.5 \) Å and dissociates to \( \text{N}^+ + \text{N}^- \). Since the projectile is doubly charged, it is likely that it would have a strong polarising effect on the \( \text{N}_2 \) which may in turn favour transitions to the \( b \) state. In addition, this state is a singlet-singlet state, the \( x \rightarrow b \) transition is a singlet–singlet transition, obeying the spin-selection rule for collisions involving a bare nucleus. As previously mentioned, such selection rules have been observed (Moore and Doering 1970, Moore 1973) for collisions between protons and molecules at energies comparable to ours and by Sato et al. for Li\(^+\) on \( \text{N}_2 \). However, in cases involving one electron outside a closed shell (e.g., incident \( \text{H}_2^+ \)) or a single electron
Scattering of He$^{2+}$ from N$_2$

Figure 2. Exit-channel spectra for elastic and inelastic He$^+$ + N$_2$ scattering.

missing from a closed shell (Ar$^{+}$) singlet-triplet as well as singlet-singlet transitions have been observed (e.g., Fernandez et al 1975). This is observed here also since we took He$^+$ + N$_2$ → N$_2^+$ ECS, shown in figure 2, for comparison with our He$^{2+}$ + N$_2$ data. In these spectra, the elastic peak is again well resolved, but now there is a peak at $Q = -7.8$ eV (peak A') and a slight shoulder at $Q = -12.0$ eV (peak B). The peak A' has been observed by other investigators (Schowengerdt and Park 1970) and is probably due to singlet-triplet transitions in N$_2$ due to coupling of the electronic spins of the He$^+$ electron with the N$_2$ electrons. The shoulder B' is best attributed to a transition to either the C $^3\Pi_u$ or $^3\Sigma^+_g$ states. The tail of these distributions is observed to proceed smoothly out into the continuum, suggesting that some ionisation of the target is also occurring. We note that there is no clear evidence of a prominent excitation of the b' state in contrast with the case of incident He$^{2+}$ at the same energy, supporting the hypotheses of the polarisation mechanism and singlet-singlet spin selection in He$^{2+}$ + N$_2$ collisions.

4.2. He$^{2+}$ + N$_2$ charge exchange

Charge-exchange ECS for 200 eV He$^{2+}$ are presented in figure 3, and for 600 eV He$^{2+}$ + N$_2$ in figure 4, again using the binary model to calculate values of $Q$. Our conclusions are not, however, sensitive to choice of model. The main features of these spectra are now summarised. All charge-exchange ECS are considerably broader than the resolution function of the energy analyser indicating that several exit channels are active in all cases. There is a trend toward larger width with increasing $r$, but the spread is toward more endothermicity. At low $r$ (1000–1800 eV deg) exothermic channels are favoured. Within this region a peak at $Q \approx 9$ eV is prominent. The only He$^+$ state that gives rise to exothermic channels is the ground state, and this implies that the target is excited to approximately 45 eV above its ground state. At large impact parameter, charge transfer to the ground state of He$^+$ is preferred due to the large separation between the adiabatic incoming potential surface and outgoing surfaces for excited He$^+$ states. The threshold for this peak lies close to the limit of producing two N$^+$ (3P) ions, which requires 38.8 eV with zero kinetic
Figure 3. Charge-transfer exit-channel spectra for 200 eV He$^2^+$ + N$_2$.

Figure 4. Charge-transfer exit-channel spectra for 600 eV He$^2^+$ + N$_2$. 
energy for the dissociated ions. At intermediate values of $\tau$ (2000–3500 eV deg) the ECS distributions are roughly centred about $Q = 0$ eV. This is most likely due to the onset of channels associated with the excitation of He$^+\,$, though with our energy resolution it is not possible to determine this unambiguously. At large values of $\tau$ (>4000 eV deg) endothermic channels are favoured; the greater the value of $\tau$, the more endothermic the spectra. Due to the large number of overlapping exit channels in this region it is impossible to distinguish specific transitions. For all values of $\tau$, but particularly for the low and intermediate values, the right-hand tail rises fairly sharply, indicating a strong discrimination against channels at higher values of $Q$. At a given $\tau$ (e.g., $\tau = 3000$ eV deg) the right-hand tail in the 200 eV and 600 eV ECS are virtually identical (apart from normalisation) while the left-hand tail of the 600 eV ECS extends much further ($Q \approx -40$ eV) than it does in the 200 eV ECS ($Q \approx -25$ eV).

5. Comparison to atomic target spectra

In figure 5 we show some of the predominant final-state channels for He$^2^+$ + Ne, Ar and N$_2$ where the energies of molecular states for target N$_2$ are taken to be at the same internuclear separation as the N$_2$ ground state. In all cases direct excitation of the target by the incident He$^2^+$ played a minor role except at the largest values of $\tau$. In figures 6–8 we show exit-channel spectra for targets Ne and Ar, for single charge transfer (Chen 1972, Boring and Johnson 1978). These spectra have some of the same general characteristics as the N$_2$ spectra discussed. At small $\tau$, exothermic channels dominate due to curve crossing of the incident channel with the outgoing repulsive states. If the exothermic states are treated as having a Coulombic long-range repulsive force and the incident channels as having a polarisation attractive force, then the maximum in the spectra observed at small $\tau$ corresponds to a dominant transition region at internuclear distances $R = 4.8$, 3.5 and 4.1 au for Ne, Ar and N$_2$. For the target molecule, since the binary collision model is employed, we interpret this distance as being measured from one of the atomic centres of the molecule. Though the Landau-Zener curve crossing scheme is based on a two-channel description of the collision, it can be used qualitatively to describe

![Figure 5. Energy levels for He$^2^+$ + Ne, Ar and N$_2$.](image)
collisions where many channels are available (Olson and Salop 1976). This description of transitions predicts a favoured transition region for small $\tau$ for which $Q$ is positive. Channels with very small exothermic $Q$ values cross at very large values of $R$ where the coupling decreases rapidly. For charge exchange this decrease is exponential. For channels with large $Q$ values the transitions are unlikely because (a) the difference slopes of the incident and exit channels increase with increasing $Q$ or (b) they cross at such small internuclear separations that the long-range forces do not describe the collision and the channels cannot be thought of as crossing. In addition, the density of available states will play an important role in determining the shapes of observed spectra.

As $\tau$ increases the primary change in the rcs is a shift in the spectra to large $Q$, as discussed earlier for target $N_2$, where the endothermic states are being, at least in part, populated by crossings with repulsive exothermic states at smaller internuclear separations. At large $\tau$ the density of populated states is large and the spectra are relatively free of any detailed structure. In the following we concentrate on the small $\tau$ results.

The final-state level spacings for single charge transfer with targets Ar and $N_2$ are quite similar, both differing considerably from those of target Ne where the binding energy is larger. The predominant feature for target Ne is four groups of closely spaced excited states of $Ne^+$ lying close in energy to the incident channel (Siegel et al 1972). Also, the channels for two-electron transfer to excited states of $He^+$
reasonably close to the incident channel on the endothermic side. Though these latter states are unobservable in the present experiments, they may easily be populated by crossings with the repulsive outgoing states and therefore we presume they play a role in determining the final-state spectra at larger \( \tau \) for this target. The single-charge-transfer spectra as shown in figure 6 are dominated by transitions to states within the four groups at small \( \tau \). The peaks were narrow enough to be identified with transitions to particular ionic states (Siegel et al 1972, Boring and Johnson 1978, Chen 1972).

By contrast the only well-defined single-charge-transfer channel lying close to the incoming channel for targets Ar and \( \text{N}_2 \) is single charge transfer to the \( \text{He}^+ \) \( (n = 2) \) state. Because it is associated with an endothermic repulsive channel, this only plays a role at large \( \tau \) in the \( \text{eCSs} \) for these two targets. Some of the unresolved structure in the large \( \tau \) results must be due to this channel. As with target Ne, two-electron processes appear to dominate the charge-transfer spectra though Ast et al (1975) find for \( \text{He}^{2+} + \text{Kr} \) that single charge transfer to \( \text{He}^+ \) \( (n = 2) \), which is nearly resonant with the incoming channel, plays a dominant role. For both target Ar and \( \text{N}_2 \) the incident channel is nearly degenerate with a group of states lying in a continuum. Double charge transfer to highly excited states of He exists in the same region, as can be deduced from figure 5. However, as these are not repulsive outgoing channels they are not expected to be populated directly by the incoming channel. There is a possibility of populating these states via a second transition.
where curve crossings with the repulsive single-charge-transfer states occur at very large separations. Our general feeling is that double charge transfer plays a small role in determining the final-state spectra for these systems.

The ECS for single charge transfer involving target Ar are shown in figures 7 and 8 and the similarity with the previously discussed N\textsubscript{2} ECS is clear. For both these cases, as stated above, the widths of the spectra imply that a number of final states are involved. For target Ar, the maximum lies in the highly excited Rydberg states of Ar\textsuperscript{+}, with some indication of structure that might be associated with doubly excited states (Siegel et al 1972). By contrast the ECS of N\textsubscript{2} for small \( \tau \) are structureless. The onset of the exothermic, single-charge-transfer peak for N\textsubscript{2} is close in energy to the target ending up as two separate N\textsuperscript{+} (3P) ground-state ions. Therefore, there are two possibilities for describing this spectrum. First, like the Ar case, the target can be left in a highly excited Rydberg state of N\textsubscript{2}\textsuperscript{+} molecular ion. As the core of this ion is repulsive and the binding energy of the outer electron weak, there are known to be a number of repulsive N\textsubscript{2}\textsuperscript{+} Rydberg states lying above the 2N\textsuperscript{+}(3P) limit. These states are excited for instance by electron impact (Wells et al 1976, Smyth et al 1973) and have an apparent threshold close to the 2N\textsuperscript{+} limit. Alternatively, the spectra could be a result of direct excitation to a state of N\textsubscript{2}\textsuperscript{++} + e. The a \( ^3\Sigma^+_u \) state of this system lies about 43 eV above the ground state of N\textsubscript{2} at the same internuclear separation (Hurley 1962), and the a \( ^3\Pi_u \) and b \( ^3\Pi_u \) states have been observed in electron excitation spectra and have appearance thresholds in the vicinity of the position of the maximum (Franklin and Haney 1970). From a molecular

![Figure 8. Charge-transfer exit-channel spectra for 500 eV He\textsuperscript{++} + Ar.](image-url)
orbital point of view of the combined incident-ion-target system, the captured ground-state He⁺ electron would correlate with a tightly bound electron of the combined system. Therefore, the capture of a tightly bound electron leaves the system in a highly excited state of the target system in any case. For larger \( \tau \) values, charge-transfer ECS for Ar clearly indicate a tail extending to larger exothermic \( Q \) values. However, for target \( N₂ \) this does not appear in the spectra. Though states of \( N₂^+ \) are available, the high and low energy spectra indicate the same threshold in the exothermic region.

6. Differential cross sections

Differential cross sections have been determined for the scattering of 200 and 600 eV He₂⁺ on \( N₂ \). The cross sections for elastic, inelastic and charge-transfer scattering as a function of the reduced scattering angle are computed separately using equation (4). It should be noted that the integral in equation (4) extends over several exit channels in the charge-transfer cross sections, and possibly also in the simple inelastic cross section. This situation is unavoidable at our present energy resolution. Also, as has been previously noted, our absolute cross sections have been calibrated by normalisation of the elastic scattering cross section for \( He^+ + Ar \) to previous absolute data.

The differential cross sections are presented in figure 9. They are plotted in terms of the reduced coordinates \( \rho (= \theta \sin \theta \sigma(\theta)) \) against \( \tau \), where \( \sigma(\theta) \) is the differential scattering cross section in units of cm² ster⁻¹. The elastic scattering cross section is observed to drop rapidly with increasing \( \tau \) throughout the range of energies and angles studied. At small \( \tau \) the dominant processes are elastic and single-charge-transfer scattering. At larger \( \tau \) the rapid decrease of the elastic cross section brings it down to a magnitude comparable to the cross section for simple inelastic collisions, while

![Figure 9](image-url)

Figure 9. Reduced cross section against reduced scattering angle for \( He₂^+ + N₂ \). Circles, charge transfer; squares, elastic; triangles, inelastic; open figures, 200 eV; closed figures, 600 eV. Lines are reduced cross sections calculated from Bohr (a) potential and Lenz-Jensen (t.d) potential at 600 eV, but are rather independent of incident energy for the range of \( \tau \) values here.
the charge-transfer cross section remains quite large, making it approximately two orders of magnitude larger than the combined elastic and inelastic cross sections at \( \tau = 7200 \text{ eV deg} \).

If we presume that double-charge-transfer channels play a small role, then the total differential cross section, which results from an average scattering potential, is determined by the single-charge-exchange cross section. In figure 9 we compare the results to \( \rho \) against \( \tau \) plots determined from the Bohr potential and Lenz-Jensen potential (Lindhard et al. 1968, Loftager and Claussen 1969), for He on N. If the binary model applies then the experimental cross sections should be twice the calculated value due to the scattering centres in each target. Based on the Bohr potential, the impact parameter range between helium and the nitrogen atom we are discussing is about 0.8 au to 1.2 au. These distances are not too small compared to the equilibrium separation of \( \text{N}_2 \), about 2.1 au, though polarisation by \( \text{He}^{2+} \) would increase this separation somewhat prior to the collision. Therefore, one might expect the measured cross section to be somewhat less than twice the single-atom cross section (Sigmund 1976). Though the eec of the elastic channel suggests that the binary model applies, the uncertainties in the present cross section values and lack of knowledge about the double-charge-transfer channel do not permit definitive statements to be made about the magnitudes of the total differential cross section. Finally, the large charge-transfer cross section suggests that an absorbing sphere model should apply reasonably well (Olson and Salop 1976). That is, within some critical distance charge exchange occurs with near unit probability. The impact parameters considered here are all well within the transition region discussed earlier and the large transition probabilities are due to the multitude of channels crossing the incident channel.

7. Conclusions

This research was aimed at improving the understanding of the mechanism involved in ion molecule collisions. The use of \( \text{H}^{2+} \) as a probe ion has provided the means to study some of these mechanisms that might otherwise have been very difficult to observe, such as spin selection and charge transfer. Especially illuminating have been the comparisons between the scattering of singly and doubly charged helium.

The binary collision model has been shown to describe reasonably the average elastic-energy transfer. We have seen evidence of spin-selection rules in the scattering of \( \text{He}^{2+} \) by molecular nitrogen. Specifically, collisions involving \( \text{He}^{2+} \) favour transitions to molecular states of the same spin multiplicity as the initial state of the molecule. We believe that this mechanism plays a dominant role in collisions involving bare nuclei. However, when the projectile possesses one electron the number of possibilities for the final states of the target electrons increases, due to coupling with the projectile electrons. We have observed evidence that \( \text{He}^{2+} \) produces transitions in \( \text{N}_2 \) to the Coulombic \( b^+ {1\Sigma}_u^+ \) state. Since this state dissociates to \( \text{N}^+ + \text{N}^+ \), we believe that a polarisation mechanism due to the high charge state of the projectile is at least partially responsible for this transition.

The various single-charge-transfer processes observed dominated throughout the energy and angular range studied, but particularly so for the more violent collisions (large energy and scattering angle implying small impact parameter). This behaviour was consistent with the results of \( \text{He}^{2+} + \text{Ar} \) where the ionisation potential was similar, though in \( \text{He}^{2+} + \text{Ne} \), the elastic channel dominated. Charge-transfer channels leaving the He\(^+\) in its ground state produced very high excitation of
the target (about 45 eV for N₂). This shows a preference toward small |Q| at small values of τ.

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