TRANSFER IONIZATION IN FAST p-He COLLISIONS

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We separate the kinematical (KTI) and Thomas transfer ionization processes in 2.5-4.5 MeV proton-He collisions by means of a switching recoil-ion momentum spectrometer at the gas-jet target in the ion storage and cooler ring CRYRING. The ratio $\sigma_{KTI}/(\sigma_{SC}+\sigma_{TI})$, where σ_{TI} and σ_{SC} are the total transfer ionization and single-electron capture cross sections, respectively, decreases with the velocity for $v>10\ v_0$ (the Bohr velocity) and appears to approach the same asymptotic limit as the double-to-single ionization ratio in (non-Compton) photoionization (1.66 %[1]). For these velocities the Thomas TI cross section scales as v^{-11} as predicted by theory [2,3].

1 Introduction

When an electron is instantaneously removed from the He ground state, the other electron finds itself in a superposition of bound and continuum He^+ eigenstates. Åberg[1] calculated the amplitude for the continuum contribution and found a 1.66 % probability for shake-off ($\rightarrow He^{2+} + e^-$). Experimentally, very fast removal of an electron from He was first realized in x-ray photoabsorption. Indeed, it has been confirmed – through measurements of the double-to single-photoionization ratio – that the probability of emitting the other electron approaches the shake-off limit at very high outgoing electron velocities[4,5]. Andersson and Burgdörfer[6] pointed out that the photoabsorption processes must be separated from ionization by Compton scattering to ensure that the electron leaves the atom with high velocity. By the recoil-ion-momentum method Spielberger *et al.*[5] distinguished these two processes. Here we investigate if the shake-off concept can be used to describe the probability for removing the 'second' electron from He if the first electron is removed suddenly by electron transfer to a very fast proton. We measure the very small transfer ionization (TI) process and, further, separate it in its Thomas[2] p-e-e (ThTI) and Kinematical TI (KTI) contributions, by non-DC recoil-ion-momentum spectroscopy at the CRYRING gas jet target. The switched spectrometer is described in section 2. In section 3, we discuss the results and the velocity scaling of the ThTI process.

2 Experiment

The experiment is performed in the ion storage ring CRYRING[7] at the Manne Siegbahn Laboratory in Stockholm. Protons are injected into the storage ring, accumulated, accelerated, and electron cooled[8] at 2.5, 3.5, and 4.5 MeV yielding currents of 20-60 μA. The ion beam

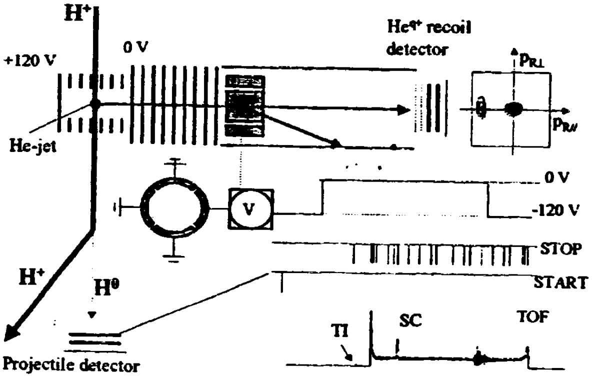

Figure 1. Details of the experimental setup as described in the text.

intersects the gas-jet target[9] (ϕ=1.0 mm and density ~10^{11} cm^{-3}) at a background pressure in the 10^{-12} mbar range. Neutral atoms formed in electron transfer processes leave the ring and are detected by a position-sensitive microchannel-plate detector, which starts a multi-hit time-to-digital converter (TDC). A homogeneous DC extraction field of 11.5 V/cm accelerates the recoil ions towards a second position-sensitive microchannel-plate detector. A fast signal from this detector serves as a stop for the TDC, which stores the time-of-flight information yielding the recoil-ion charge-state distribution. The longitudinal recoil-ion momenta are deduced from the positions along the beam on the recoil detector (cf. figure 1).

The ratio between the cross sections for TI and single ionization (SI) is very unfavorable. At our highest velocity (13.4 v_0) the SI cross section is about $6 \cdot 10^{-18}$ cm^2 [10], whereas we find a TI cross section of $(3.7\pm0.7)\cdot 10^{-26}$ cm^2. This suggests a TI rate of 1 min^{-1} and a SI rate of ~10^7 s^{-1}. It is thus essential to introduce a charge selection prior to detection, which prevents random ions from SI to reach the detector at the same time as He^{2+} from TI. This is achieved by switching off the voltage on a deflector in the spectrometer only after a neutral hydrogen atom formed in a SC or TI collision has triggered the projectile detector. The delay is chosen such that the faster He^{2+} ions from a TI event are unaffected, whereas the He^+ ions that would have reached the detector simultaneously have already been deflected away. This reduces the random level by a factor of ~400 as given by the σ_{DI}/σ_{SI} ratio[11] (DI: Double Ionization).

3 Results and discussion

In figure 2 we show a time-of-flight spectrum recorded in the time-switched mode. The zero-point is the time of H^0-detection. Before t=4.2 μs only detector noise is observed, then there is an increase to a level set by random coincidences from DI events, on top of which the TI peak is seen at t=4.6 μs. At t=5.2 μs the random level increases dramatically as the first He^+ ions from SI reach the detector. The peak at t=6.7 μs is due to SC events. The relative detection efficiency for He^+ and He^{2+} ions was obtained through normalization at 0.3 MeV to the $\sigma_{TI}/(\sigma_{SC}+\sigma_{TI})$ ratio by Mergel et al.[12] yielding (83.3±6.5) %. The ratios $\sigma_{TI}/(\sigma_{SC}+\sigma_{TI})$ were then extracted from the time-of-flight spectra for measurements at 2.5, 3.5, and 4.5 MeV. The absolute cross section scale was determined through the total electron capture cross sections by Schwab et al[13].

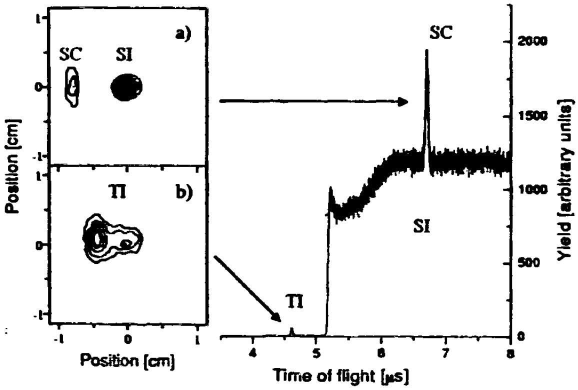

Figure 2. The right part of the figure shows the time-of-flight spectrum recorded in the time-switched mode with 2.5 MeV protons. At the position of the TI peak there is only a weak random signal from DI, whereas the SC peak rides on the large SI random level. Inset a) shows a contour plot of the recoil-positions recorded in coincidence with the SC peak. Inset b) is the equivalent picture for the TI peak.

We distinguish between KTI and the Thomas p-e-e TI mechanism through their different recoil-ion-momenta along the projectile axis as deduced from the position distribution of the TI recoil ions. The inset a) in figure 2 shows the density of hits on the recoil-ion detector for a narrow time window around the SC peak. The maximum to the left is due to true SC events, whereas the wider peak is due to SI randoms. The inset b) shows the recoil-ions from TI. The structure to the left stems from the KTI process, whereas the distribution closer to the detector's center is mainly the Thomas p-e-e scattering process with a small contribution from DI randoms. The latter part was isolated in a separate measurement in which a random pulse generator started the TDC yielding a time-of-flight spectrum without real coincidences. Figure 3 shows the ratio of TI to the total capture cross section as a function of the proton velocity showing also results from Shah and Gilbody[14] and Mergel et al[12]. In the latter and the present experiment Thomas TI was isolated and the $\sigma_{KTI}/(\sigma_{SC}+\sigma_{TI})$ ratios are shown as open symbols. Our $v > 10\ v_0$ data show a decrease with increasing velocities in contrast to the trend for $v < 10\ v_0$[12]. The probability for emission of the second electron following electron transfer approaches the shake-off limit 1.66 %[1,6].

The present absolute cross sections for the Thomas p-e-e mechanism are shown in figure 4 together with the results of Mergel et al.[12] and Shah and Gilbody[14] at lower proton velocities. The line in figure 4 has a slope corresponding to a v^{-11} velocity dependence, consistent with the theoretical predictions[2,3] at high v. Note also that the present data for $v > 10\ v_0$ fall off much more rapidly with v than the previous data for $v < 10\ v_0$ (cf. ref 12).

4 Conclusions

Here, we have investigated the TI process for fast p-He collisions in the range 2.5-4.5 MeV where the cross section becomes $\sim 10^3$ times lower than at the previous highest energy (1.4 MeV[12]). The $\sigma_{TI}/(\sigma_{SC}+\sigma_{TI})$ and $\sigma_{KTI}/(\sigma_{SC}+\sigma_{TI})$ ratios are decreasing with v in the range $10.0\ v_0 < v < 13.4\ v_0$ and the latter ratio seems to be approaching the shake-off limit 1.66 %[1,6]. The present high-velocity cross sections for the Thomas p-e-e transfer ionization process are consistent with a v^{-11} scaling[2,3].

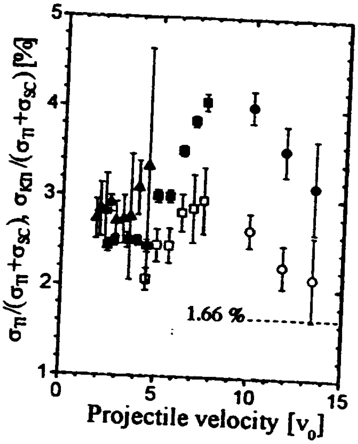

Figure 3. The ratios of TI to total electron capture (▲ Shah and Gilbody[14], ■ Mergel *et al.*[12], ● present work) and the ratio of the kinematical transfer ionization process (KTI) to the total capture (□ Mergel *et al.*[12], ○ present work) as function of the projectile velocity. The latter ratio is expected to approach the 1.66 % shake-off limit for $v \gg v_0$.

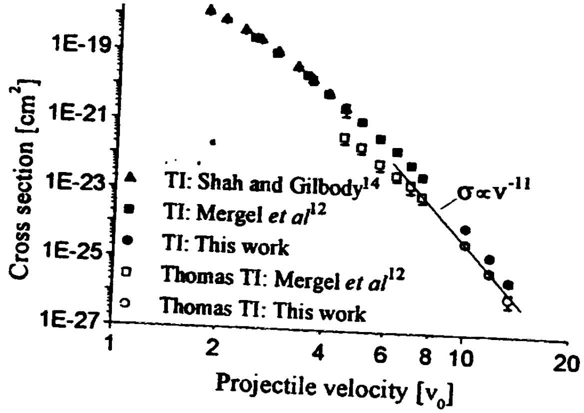

Figure 4. The total TI (▲ Shah and Gilbody[14], ■ Mergel *et al.*[12], ● present work), and Thomas p-e-e TI (□ Mergel *et al.*[12], ○ present work) cross sections as functions of the projectile velocity. The line through the present Thomas p-e-e TI data points (○) has a slope corresponding to a v^{-11} velocity dependence.

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