Removing random event s due to single ionization in measurements of transfer ionization in fast p-He collisions

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We have measured the recoil ion momentum distributions for five different reaction processes in proton-He collisions in the energy range 2.5-4.5 MeV[1]. There are two main difficulties involved in these measurements. First, it is expected that the absolute cross sections for the Transfer Ionization (TI) processes $H^+ + He \rightarrow H^0 + He^{2+} + e^-$, the Kinematical- (KTI) and the Thomas-TI processes (distinguished through their different longitudinal recoil ion momenta), are very small – of the order of a few times 10^{-26} cm^2 at 4.5 MeV[2]. Second, the cross section for pure single ionisation (SI) is about nine orders of magnitude larger at this energy. The high luminosity required to deal with the first problem is achieved through multi-turn injection, ion stacking, electron cooling and acceleration of protons in the heavy ion-storage ring CRYRING[3] at the Manne Siegbahn Laboratory in Stockholm. The stored, intense (~30 μA), proton beam intersects a pre-cooled (90 K), dense (10^{11} cm^{-3}), and collimated (ϕ=1 mm) supersonic He gas-jet target[4] yielding a luminosity of ~10^{24} cm^{-2}s^{-1} at a negligible increase in the ring base vacuum pressure (10^{-12} mbar range). From the expected TI and SI rates of 10^{-2} and 10^7 s^{-1}, respectively, it is clear that continuos recoil ion extraction and momentum analysis at fixed spectrometer voltages (DC) would lead to a situation in which random events from single ionization would make it practically

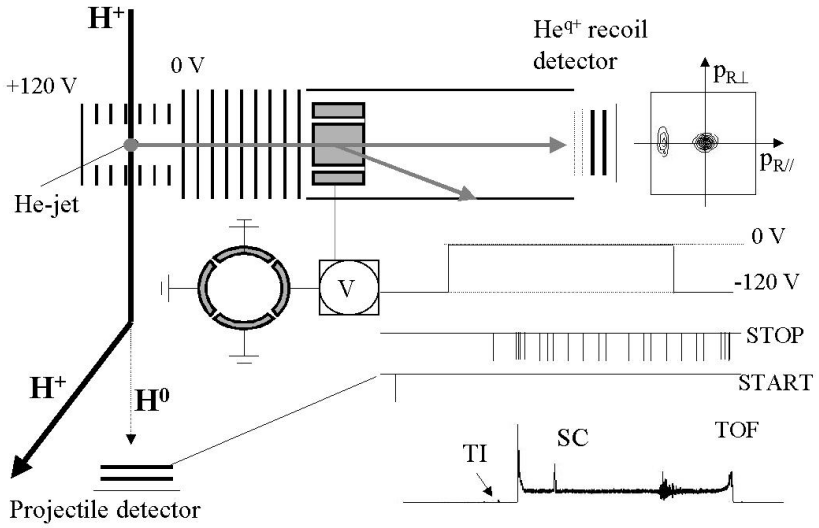

Figure 1: A schematic of the switched recoil-ion momentum spectrometer (cf. text).

impossible to isolate the TI-events. In figure 1, we show our solution to this problem. Neutral hydrogen atoms (H^0) leave the storage ring at the first bending dipole magnet after the gas-jet target and are detected by a multichannelplate detector followed by a resistive anode. The fast pulse from the back of the second channelplate is used to start a multi-stop Time-to-Digital Converter (TDC) and to set the voltage of the deflector in the spectrometer to 0 V after a preset delay (of around 1.5 μs depending on the beam energy). The exact value of this delay is chosen as to let the He^{2+}-recoils from TI events through without deflection (normally the deflector is set to –120 V and all recoils are deflected to the spectrometer wall). At the time of switching there are typically 10-20 He^+ ions (randoms) on the way towards the deflector. They are, however, slower than the He^{2+} -ion (from TI) and will thus arrive *at a later time* at the detector. This can be seen in figure 1 where the very small TI-peak sits on a small background due to random events from double ionization. After about 0.5 μs there is a sharp rise in the random level due to the arrival of the 'first' He^+ from single ionization. The peak at this time is due to the forward acceleration of He^+ ions in the fringe field of the deflector (negative voltage) just before switching and is followed by a flat level due to single ionization randoms. On top of this level there is a peak due to single-electron capture (SC). The switched deflector is open for 10 μs which also is the duration of the high single ionization random level in the Time-of-Flight (TOF) spectrum. The SC peak is of course due to real coincidence events in which the start pulses were given by $H^+ + He \rightarrow H^0 + He^+$ neutralization yielding He^+ recoils with fixed time relations to the start pulses. As an inset we show a recoil-ion momentum image on the recoil detector with a gate set on the time-of-flight peak for single-electron capture (SC). The center peak at ($p_{R//}=0$, $p_{R\perp}=0$) is due to the momentum distribution of single ionization (the random contribution within the gate) while the peak to the left is due to single electron capture with longitudinal momentum $p_{R//}=-Q/v - v/2 \approx -v/2$.

In the experiment, we distinguished between the Kinematical and Thomas TI processes ($p_{R//} \approx -v/2$ (KTI) and $p_{R//} \approx 0$ (Thomas)) and established the ratios σ_{KTI}/σ_{SC} as functions of the collision velocity v. A remaining instrumental problem for the separation of the two TI-processes was pile-ups of the slow (μs) position signals from the resistive anode. This was dealt with by sorting the multi-stop list mode data to make sure that each position-analyzed TI event had a certain minimum time to the next following random SI event.

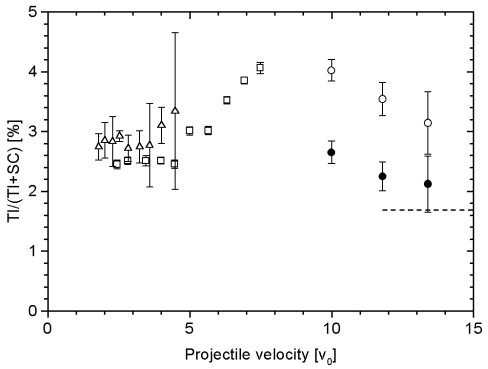

Figure 2. The ratio of TI to total electron capture. The open triangles are the results of Shah and Gilbody[8]. The open squares are from the measurement of Mergel et al[7]. The open circles show the present results for the ratio of TI to total capture. The ratio of the KTI process to the total capture is shown as filled circles.

The results show (figure 2) that the $\sigma_{KTI}/(\sigma_{SC}+\sigma_{TI})$ ratio decreases with v and appears to approach the photoionization shake-off limit of 1.7 %[5,6] for v>10 a.u.. This result contrasts to earlier data by Mergel *et al* on $\sigma_{TI}/(\sigma_{SC}+\sigma_{TI})$ were σ_{TI} is the total TI cross section $\sigma_{TI} = (\sigma_{KTI}+\sigma_{TI}^{Thomas})$ with only smaller contributions from σ_{TI}^{Thomas} showing an increase with v in the lower velocity region v<10 a.u.[7]. We also find that the absolute σ_{KTI} cross section scales with velocity as v^{-11} for higher velocities again in contrast with the results of Mergel *et al*[7] at lower v but in agreement with the theoretical prediction by Briggs and Taulbjerg[2].

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