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Electron–electron interaction in projectile ionization

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Abstract

For simultaneous projectile and target ionisation in He^+–He collisions the momentum distribution of the singly and doubly charged recoil ions has been measured. A new cold target recoil ion momentum spectrometer with a momentum resolution of ±0.13 a.u., based on a precooled supersonic He gas jet, has been used. The experimental doubly differential cross section shows two prominent structures which can be attributed to the two center electron–electron interaction and the nucleus–electron interaction. The contribution due to the electron–electron interaction is found to be negligible at 0.5 MeV impact energy and to be dominant at 2 MeV. The two center electron–electron interaction contributes much less to target double than to single ionisation.

1. Introduction

In a fast ion atom collision where the projectile carries at least one electron a two-center electron–electron interaction (ee) can lead to an ionisation of both collision partners [1]. In a competitive process this ionisation can also be caused by a nucleus–electron interaction (Ne). Most experimental attempts to separate the two processes of (ee) and (Ne) interaction were so far restricted to total cross section measurements [2–4]. Only Montenegro and coworkers reported scattering angle dependent cross sections [5]. The very different role of the target nucleus in the two processes, however, allows a direct experimental approach to this problem. While for the (ee) interaction the two nuclei are passive spectators to the process, they are actively involved in the case of an (Ne) interaction. Thus one can expect distinct momentum transfer to the remaining target ion for both processes. In this work we have therefore measured the momentum distribution of the recoil ions in direction parallel ($p_{\parallel rec}$) and perpendicular ($p_{\perp rec}$) to the ion beam for the reactions:

$$0.5\text{–}2\ \text{MeV}\ He^+ + He \rightarrow He^{2+} + He^+ + e^-, \qquad (1)$$

$$0.5\text{–}2\ \text{MeV}\ He^+ + He \rightarrow He^{2+} + He^{2+} + 2e^-. \qquad (2)$$

A part of the results has already been published [6]. A parallel study for highly charged ions impinging on helium has been performed by Wu and coworkers [7].

2. Experiment

The experimental separation of the (ee) and (Ne) interaction requires a resolution far below 1 a.u. for the momentum determination of the recoil ions. This has been achieved by a cold target recoil ion momentum spectrometer (COLTRIMS), which is based on a precooled supersonic gas jet. The target gas expands at a pressure of 200 mbar through a 30 μm hole into a first chamber pumped by a 360 l/s turbo molecular pump. The target gas and the gas outlet are cooled to 20 K on a cryogenic cold head. The coldest innermost part of this gas jet passes through a 0.3 mm diameter skimmer into the collision chamber. The resulting cold gas jet has a diameter of 1.1 mm at the

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collision point and an internal momentum spread of around 0.05 a.u. perpendicular to its direction of propagation. The jet leaves the collision chamber into a separately pumped jet dump. The gas jet intersects with the He^+ ion beam from the 2 MV van de Graaff accelerator of the Institut für Kernphysik of the University Frankfurt. The ion beam is collimated by two sets of adjustable slits upstream of the reaction chamber. It is purified from charge state contamination from reactions with the residual gas in the beam pipe by electrostatic deflectors about 20 cm upstream of the target. Downstream of the target the beam is charge state analysed by another electrostatic deflector and detected by a two dimensional position sensitive channel plate detector. The recoil ions created at the intersection point of gas jet and ion beam are accelerated in a weak homogeneous electric field (0.33 V/cm), pass through a field free drift region and are detected by a position sensitive channel plate detector with a position resolution of 0.2 mm. From the time of flight the recoil ion charge state and its momentum component in the field direction can be obtained. The two momentum components perpendicular to the field direction are calculated from the position on the channel plate detector. A more detailed description of the spectrometer can be found in Ref. [8]. With this recoil ion momentum spectrometer a resolution of ± 0.13 a.u. is obtained.

3. Results

The measured He^+ recoil ion momentum distribution (reactions (1)) for 1 MeV impact energy shows two distinct peaks, reflecting the two reaction mechanisms of (ee)

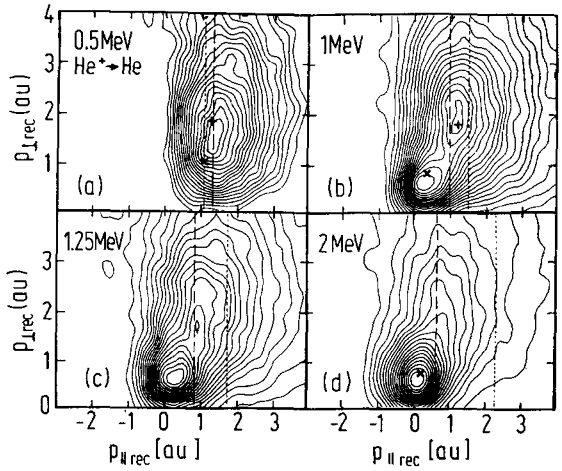

Fig. 1. Double differential cross sections for reaction (1). The y-axis shows the momentum of the recoiling He^+ ion perpendicular to the beam axis and the x-axis the momentum in beam direction (positive value means forward emission). The long dashed line shows the estimated position of the (Ne) interaction.

and (Ne) interaction. In the following we will discuss (a) the $p_{\parallel rec}$, (b) the $p_{\perp rec}$ and (c) the energy dependence of the contributions of the two mechanisms.

(a) Seen in the laboratory system the energy which is necessary for the ionisation of the projectile (binding energy of $E_b = 2$ a.u. plus the continuum energy in the projectile system E_c) is taken from the kinetic energy of the projectile. This results in a change of projectile momentum $\Delta p_{pro} = (E_b + E_c)/v_{pro}$. In the case of an (Ne) interaction Δp_{pro} is compensated by the target nucleus, throwing the recoil ion forward. The position is marked by the long dashed line in Fig. 1 assuming $E_c = 0$. In the case of an (ee) interaction this momentum is compensated by the momentum of the ejected target electron, throwing this electron strongly forward but leaving the recoil ion nearly at rest.

(b) In the perpendicular direction the recoil ion momentum is mostly dominated by the internuclear repulsion and thus reflects the impact parameter [9–11]. Montenegro and Meyerhof [12] calculated that the (Ne) process will have its maximum contribution from impact parameters around the He^+ shell radius contrary to the (ee) process which peaks at larger impact parameters, since the nuclei are not directly involved. Our data confirm this prediction.

(c) Fig. 1 shows that the (ee) and the (Ne) interaction have a very different energy dependence. At low energies the (ee) interaction does not contribute and at the highest energy the contribution due to the (Ne) interaction vanishes. The threshold behaviour of the (ee) interaction is well expected [2,3]. For the present collision system the He^+ binding energy results in a threshold for electron impact ionisation corresponding to a velocity of 0.4 MeV He. The (ee) contribution results from a first Born type process. Therefore, the cross section can be expected to fall in the high energy limit like $1/E \ln E$. The (Ne) contribution however requires an interaction of the target nucleus with the projectile electron and a second interaction of the projectile nucleus with the target electron. It can therefore be expected to fall in the high energy limit like $1/E^2 \ln E$ [3]. Two center nCTMC calculations [6] show that at the lowest energy a third mechanism will contribute significantly to the cross section. It predicts a three step mechanism: double ionisation of the target by the projectile followed by a capture of the projectile electron by the target nucleus. The calculations are shown in Fig. 2.

For reaction (2) even more mechanisms become possible. The second target electron can be ionized by the interaction with any of the two other electrons or by an independent interaction with the projectile. These various processes cannot however clearly be separated experimentally. The momentum distributions of the He^{2+} recoil ions are shown in Fig. 2 for two different impact energies. The He^{2+} recoil ions are found at much larger perpendicular momenta than the He^+ ions, showing that smaller impact parameters are necessary to doubly ionize the target. At 1 MeV the shoulder at small $p_{\perp rec}$ which results from the contribution of the (ee) interaction in the creation of He^{+} recoil ions does not show up in the data for He^{2+} ions. As could be expected the (ee) interaction at distant collisions mostly does not lead to target double ionisation.

At 0.5 MeV, where the (ee) contribution is negligible, the He^{2+} recoil ions are a little more forward shifted than the He^{+} ions. This is probably due to the higher binding energy of the second target electron. For zero continuum

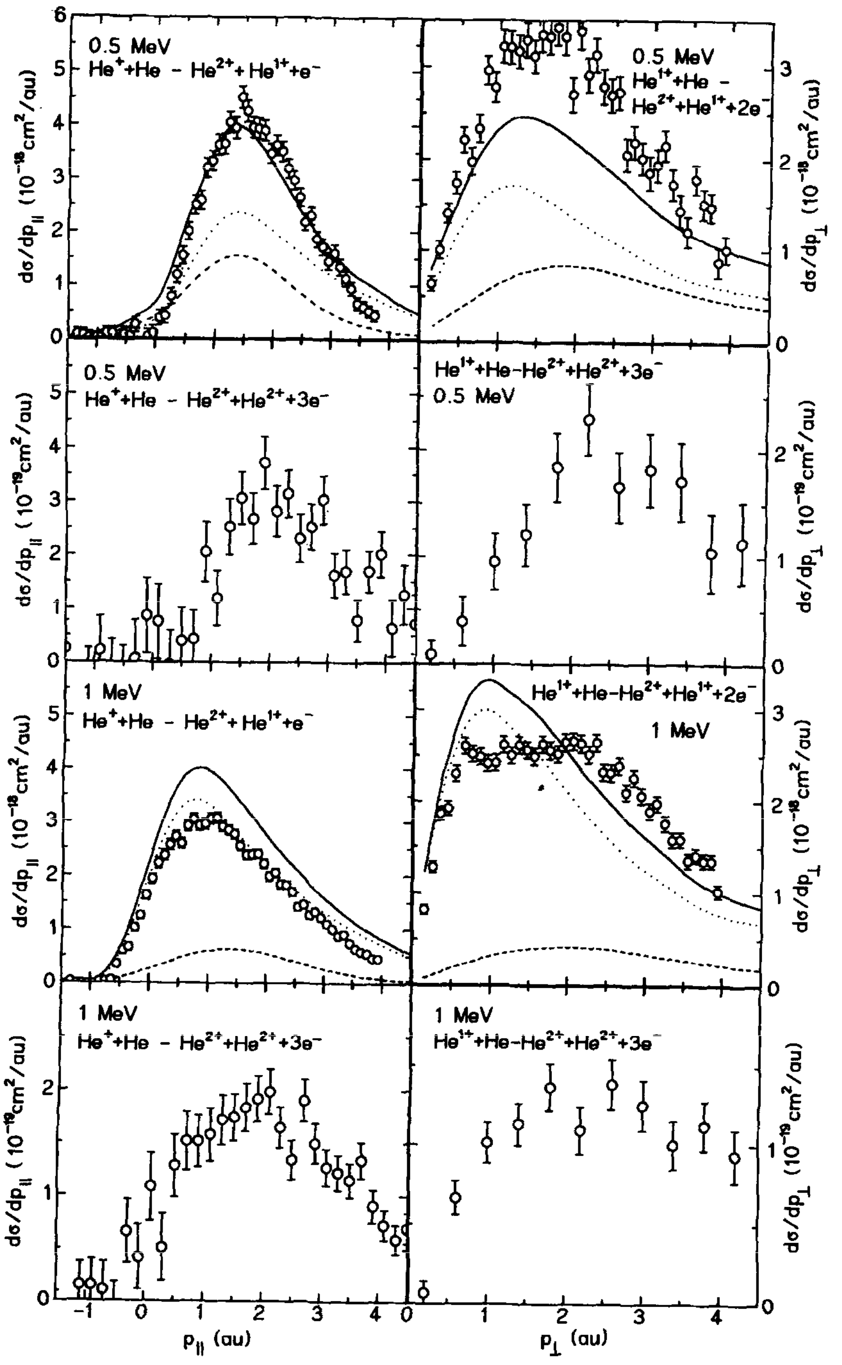

Fig. 2. Single differential cross sections for reactions (1) and (2). Left column: longitudinal momentum distribution. Lines: two center nCTMC calculation; dotted line: sum of (ee) and (Ne) contribution; dashed line: double ionisation plus capture (see text); full line: sum over both processes. Right column: perpendicular momentum distribution.

energy of the electron this would lead to a forward shift of $E_b/v_{pro} = 0.8$ a.u. The measured shift is much smaller than this, indicating that this momentum is partly compensated by the continuum momentum of the electron itself [13,10].

In conclusion, we have experimentally separated the contribution of the two center electron–electron interaction in simultaneous projectile and target ionisation by using cold target recoil ion momentum spectroscopy. Experiments are under preparation to also prove the mechanism of target double ionisation plus capture of the projectile electron by the target, which is predicted by two center nCTMC calculations [6].

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