Nuclear Instruments and Methods in Physics Research B 99 (1995) 111–113

ELSEVIER

NIM B
Beam Interactions with Materials & Atoms

Capture, ionisation and loss in swift $He^{1,2+}$–He collisions investigated by cold target recoil ion momentum spectroscopy ☆

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Abstract

For 0.25–2MeV He^{2+}–He and He^{+}–He collisions we have measured the recoil ion momentum distribution in three dimensions for single capture, target ionisation and projectile electron loss. From these double differential cross sections we obtain state selective and scattering angle dependent cross sections for the single capture process and are able to distinguish between electron–electron and nucleus–electron interactions for the projectile electron loss.

1. Introduction

Swift ion atom collisions allow for a richness of different electronic processes like target ionisation, projectile ionisation, single and multiple electron capture or transfer ionisation. Each of these processes which are characterized by the charge states of the reaction products are governed by very different momentum exchange processes between the particles involved. In this work we take a fresh look on some of these processes from the point of view of the momentum transfer to the recoil ion. For example in a pure capture reaction the change in momentum experienced by the projectile must be compensated by the recoil ion, since there are only two particles in the final state. Thus a measurement of the momentum of the ion transverse to the beam ($p_{\perp_{rec}}$) is equivalent to a determination of the transverse momentum of the projectile, i.e. the scattering angle. The measurement of the recoil ion longitudinal momentum (in beam direction) ($p_{\|_{rec}}$) is equivalent to projectile energy gain spectroscopy. The advantage of detecting the momentum of the recoil ion instead of the change of the projectile momentum is a tremendous increase in resolution since the accuracy of the projectile measurement is restricted by the quality of the preparation of the huge initial momentum p_{pro} [1–3]. The typical final state recoil ion momenta in the processes listed above are in the range of a few atomic units (au). For the experiments we have used a cold target recoil ion momentum spectrometer (COLTRIMS) based on a precooled supersonic gas jet. The apparatus has a momentum resolution of ± 0.13 au. For a single capture reaction of 1 MeV He^{2+} on He this corresponds to a scattering angle resolution of $\pm 7 \times 10^{-6}$ rad and an accuracy in the energy gain measurement of $\Delta E/E_{pro} = \pm 2 \times 10^{-5}$. A description of the apparatus can be found in Refs. [3,4]

2. Results and discussion

Fig. 1 shows the measured $p_{\|_{rec}}$ distribution for the following reactions:

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

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

$$0.5\ \text{MeV}\ He^{+} + He \rightarrow He + He^{+}, \quad (3)$$

$$0.5\ \text{MeV}\ He^{2+} + He \rightarrow He^{+} + He^{+}. \quad (4)$$

☆ The work was financially supported by DFG, BMFT and DOE grant 82ER53128. One of us (W.E.M.) was supported by NSF grants INT-9013087 and PHY-9019293. W.W. and C.L.C. acknowledge financial support from Max Planck Forschungspreis of the Humboldt foundation which made their visit to Frankfurt possible.

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SSDI 0168-583X(94)00672-5

The various reaction channels show very different momentum transfer to the recoil ion. In general the recoil ions formed in a loss process are found to be emitted in the forward direction, the ions from a reaction with no change in charge for the projectile are found close to zero longitudinal momentum with a width of around 1 au. The ions resulting from capture reactions show line structure and are backward directed.

The longitudinal momentum of the recoil ion can be calculated from energy and momentum conservation to be [4]:

$$p_{\parallel_{\mathrm{rec}}} = p_{\parallel_{\mathrm{rec}}}^{\mathrm{capture}} + p_{\parallel_{\mathrm{rec}}}^{\mathrm{ionisation}} + p_{\parallel_{\mathrm{rec}}}^{\mathrm{loss}}, \tag{5}$$

$$p_{\parallel_{\mathrm{rec}}}^{\mathrm{capture}} = -\frac{n_{\mathrm{c}} m_{\mathrm{c}} v_{\mathrm{pro}}}{2} + \frac{Q_{\mathrm{c}}}{v_{\mathrm{pro}}}, \tag{6}$$

$$p_{\parallel_{\mathrm{rec}}}^{\mathrm{ionisation}} = \sum_{k=1}^{n_{\mathrm{i}}} \frac{E_{\mathrm{bind}}^{k} + E_{\mathrm{cont}}^{k}}{v_{\mathrm{pro}}} - p_{\parallel}^{\mathrm{e}_k}, \tag{7}$$

$$p_{\parallel_{\mathrm{rec}}}^{\mathrm{loss}} = \sum_{j=1}^{n_{\mathrm{i}}} \frac{E_{\mathrm{bind}}^{j} + E_{\mathrm{cont}}^{j}}{v_{\mathrm{pro}}}. \tag{8}$$

n_{c}, n_{i} and n_{l} are the number of captured, ejected target and projectile electrons. Q_{c} gives the differences in binding energy in the initial and final state summed over all captured electrons, E_{bind} and E_{cont} are the binding and continuums energies of the target and projectile electron in their parent rest frame and $p_{\parallel}^{\mathrm{e}_k}$ is the longitudinal momentum of target electron k in the final state.

2.1. Electron capture

Eq. (6) shows that for a pure capture reaction $p_{\parallel_{\mathrm{rec}}}$ consists of one part proportional to the projectile velocity, which is due to the mass transfer from the target to the projectile, and a second part which reflects the momentum change of the projectile due to the Q value of the reaction. Therefore only discrete values of $p_{\parallel_{\mathrm{rec}}}$ are allowed, which are connected to the capture to different projectile final states. The present resolution of ± 0.13 au allows to separate K shell capture from capture to exited states for reaction (4). Additionally Fig. 1d shows a small third peak which results from capture to an exited state plus target exitation. Like in translational spectroscopy for a symmetric collision system the experiment can not distinguish between the target or the ejectile being in the exited state. It has been shown theoretically [5] that the cross section for target exitation is very small compared to capture to an exited state. As outlined in the introduction the perpendicular momentum of the recoil ion in a pure capture reaction

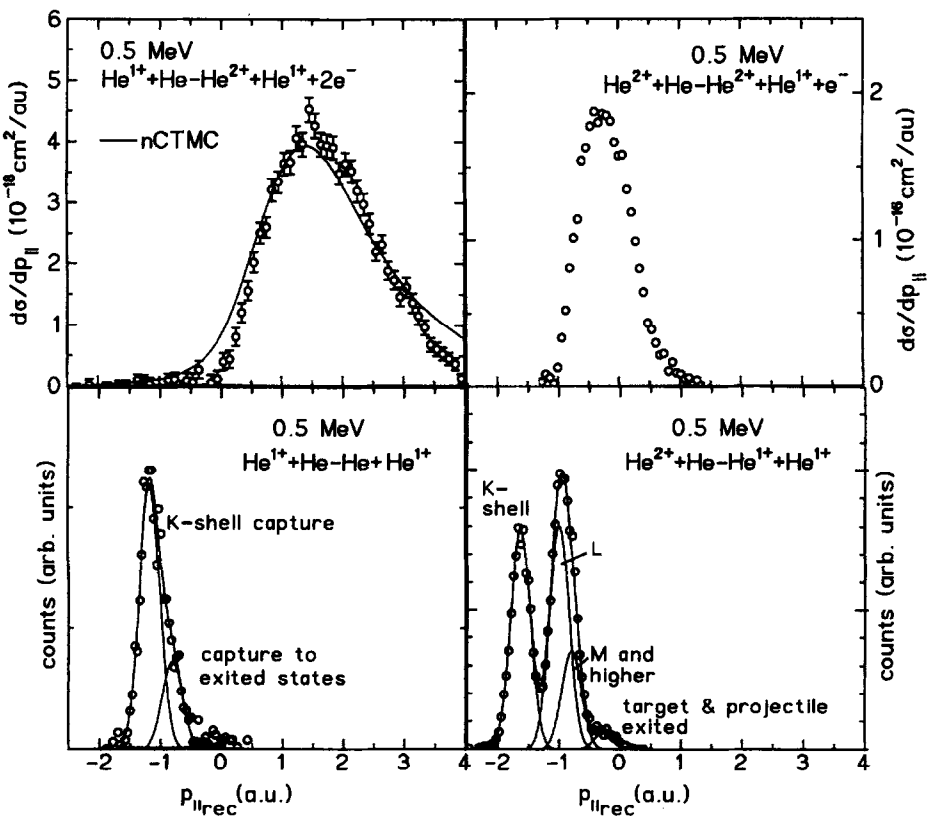

Fig. 1. Longitudinal momentum distributions (i.e. in direction of the ion beam) of the recoil ions from reactions (1)–(4).

is equivalent to the projectile scattering angle. The measured scattering angle differential cross sections for reaction (4) are shown in Fig. 2. The lower scale of the x-axis gives the recoil ion transverse momentum and the upper scale the corresponding projectile scattering angle. For the K-shell capture we find a structure in the differential cross section which is due to the interference of the transition amplitudes for K–K vacancy transfer in a quasi molecular approach [6]. It is surprising however, that this interference pattern appears for 0.5 MeV impact energy and $v_{pro}/v_e = 2.7$.

2.2. Projectile ionisation

Reaction (1) involves projectile ionisation with simultanious target single ionisation. For this process two mechanisms have been proposed [7,8]. The projectile electron interacts with one of the target electrons (ee); or the projectile nucleus interacts with the target electron and in a second step the projectile is ionized by an interaction with the target nucleus (2Ne). The measurement of the momentum of the recoil ion gives a direct signature to distinguish between these two mechanisms. In the case of the (ee) interaction the target nucleus is only a spectator to the process which will lead to recoil ions with nearly zero momentum. For the (2Ne) process sufficient momentum must be transfered between target nucleus and projectile electron to overcome the binding. For 1 MeV impact energy (Fig. 3b) the two dimensional momentum distribution of the recoil ions shows two maxima which can be attributed to the (ee) and the (2Ne) process. For the (ee) process a threshold can be expected at 0.4 MeV (equivalent to an electron energy of 54 eV). Therefore in Fig. 3a the maximum close to zero momentum disappears. For 0.5

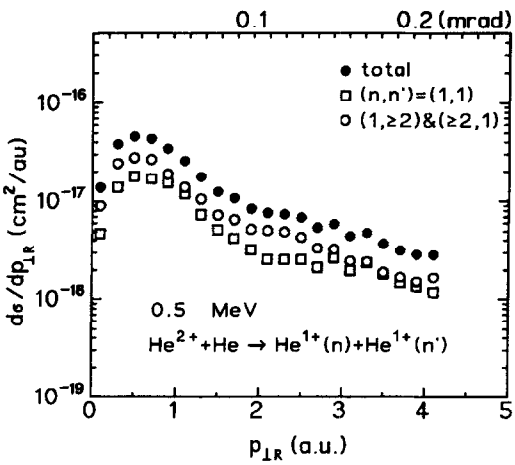

Fig. 2. Differential cross sections for single capture in 0.5 MeV He^{2+}–He collisions. Squares: ground state capture, circles: capture to an excited state, full dots: total capture. Lower scale transverse momentum of the ion, upper scale projectile scattering angle.

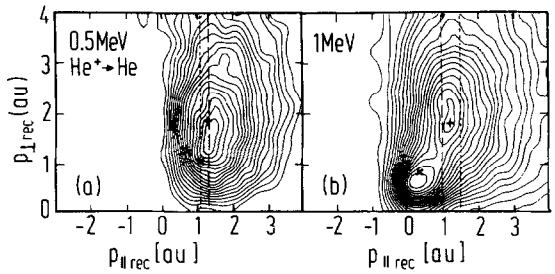

Fig. 3. Longitudinal (to the ion beam) and transverse momentum distribution of He^+ recoil ions from simultanious target and projectile ionisation. The peak close to zero at 1 MeV is due to the (ee) interaction, the second peak is due to the (Ne) interaction.

MeV impact energy the $p_{\parallel_{rec}}$ distribution (Fig. 1a) is dominated by the $p_{\parallel_{rec}}^{loss}$ term. In the case of an (ee) interaction this forward momentum is compensated by $p_{\parallel}^{e}$. A more detailed discussion can be found in Ref. [4]. A parallel study for highly charged ion impact has been reported by Wu et al. [9].

3. Conclusion

We have demonstrated the diversity of momentum transfer to the target nucleus for different reaction channels and reaction mechanisms in ion–atom collisions. That is what makes COLTRIMS a unique experimental tool in this field. In particular we have shown the power of COLTRIMS to deliver state selective and scattering angle differential cross sections for electron capture and its ability to distinguish between the (ee) and the (Ne) interaction for simultanious target and projectile ionisation.

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