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Projectile focusing near the recoil-ion threshold

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Abstract. The post-collisional interactions in ion-atom ionization collisions are studied around the electron capture to the continuum (ECC) process. For this purpose, a suitable double differential cross section is introduced, involving the longitudinal recoil-ion momentum and the projectile transverse momentum transfer. Using the fact that the ECC process is closely related to the threshold in the longitudinal momentum distribution, we study this distribution as a function of the projectile scattering angle. Using the CDW-EIS approximation we theoretically find a focusing (defocusing) effect as we get closer to the distribution threshold for proton (antiproton) impact on He atoms.

1. Introduction

Quite recently a renewed interest in ion-atom ionization collisions has been triggered by previous advances in experimental techniques that have made it possible to go beyond the electron spectroscopy and measure cross sections differential in the projectile and recoil ion momenta [1-3]. The relation between the recoil-ion spectroscopy and the electron spectroscopy have been discussed in detail in the past [4,5]. In this work we are interested in analysing whether the projectile scattering can be affected by the interaction with the emitted electron or not, and to what extent. To this end, we perform a simultaneous analysis of both the projectile scattering angle and the longitudinal recoil-ion momentum distribution. This doubly differential cross section (DDCS) has the advantage of allowing the study of the projectile scattering when the electron capture to the continuum (ECC) is dominant [4]. In fact, when the longitudinal recoil-ion distribution approaches its threshold, the emitted electron velocity reaches that of the projectile. Under these conditions, the final-state projectile-electron interaction is dominant. As first proposed in [6,7], one could expect the projectile to be focused in the forward direction by an attractive projectile-electron interaction (positive ion impact), or alternatively defocused by a repulsive interaction (antiproton impact).

In this work we study this effect in a quantitative way by analyzing the mean value of the projectile scattering angle as a function of the longitudinal recoil-ion momentum. In section 2 we summarize the main expressions to be used. The results are discussed in section 3. Atomic units are used throughout this paper.

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2. Theory

The final state in the single ionization of atoms by ion impact is characterized by the nine momentum components of the three intervening particles: the projectile, the target nucleus and the emitted electron. Due to momentum and energy conservation during the collision, only five components are independent. For heavy-ion collisions, the quintuple differential cross section relating the projectile transverse momentum transfer ($\vec{\eta}$) and the electron emission angles (θ_e, ϕ_e) and energy (ε_e) reads

$$\frac{d^5\sigma}{d\vec{\eta}\; d\varepsilon_e\, d(\cos\theta_e)\, d\phi_e} = \frac{\mu^2}{4\pi^2 v^2}\, p_e \left|T_{if}\right|^2 \tag{1}$$

Here, $\vec{v}$ is the velocity of the projectile, $\vec{p}_P = \vec{k}_i - \vec{k}_f = \vec{p}_P \cdot \hat{v} + \vec{\eta}$ is the momentum transfer, where $\vec{k}_i$ ($\vec{k}_f$) is the initial (final) momentum of the projectile, μ is the reduced mass and T_{if} is the transition amplitude.

In order to write the quintuple differential cross section in terms of the recoil-ion momentum $\vec{p}_R$, the energy-momentum conservation is used [8]. The longitudinal momentum balance for the three particles along the incident beam direction is given by

$$p_{P\|} = p_{R\|} + p_{e\|} = (\varepsilon_e + |\varepsilon_i|)/v \tag{2}$$

where $p_{R\|}$ is the longitudinal recoil ion momentum and $\left|\varepsilon_i\right|$ is the `binding energy' of the target atom in the initial state. This expression is correct to the order of $O(1/M_P)$ and $O(1/M_T)$ where M_P (M_T) is the mass of the heavy projectile (target). This equation can be cast to the form [4,5]

$$p_{R\|} = -\frac{v}{2} + \frac{|\varepsilon_i|}{v} + \frac{(\vec{p}_e - \vec{v})^2}{2v} = -\frac{v}{2} + \frac{|\varepsilon_i|}{v} + \frac{p_e^2 + v^2 - 2p_e v\cos\theta_e}{2v} \tag{3}$$

By using this relation we change from the variable $\cos\theta_e$ to $p_{R\|}$ in equation (1). Finally we integrate over ϕ_e and ε_e in order to obtain the DDCS

$$\frac{d^2\sigma}{d\theta_P dp_{R\|}} = 2\pi k_i^2 \theta_P \int_{\varepsilon^-}^{\varepsilon^+} d\varepsilon_e \int d\phi_e \frac{d^5\sigma}{p_e d\vec{\eta}\, d\varepsilon_e d(\cos\theta_e)\, d\phi_e} \tag{4}$$

where $\varepsilon^{\pm} = p_e^{\pm 2}/2$, $p_e^{\pm} = v\cos\theta_e \pm \sqrt{v^2\cos^2\theta_e + 2(p_{R\|}v - |\varepsilon_i|)}$ and $\eta = k_i\theta_P$ $(\theta_P << 1)$. From this DDCS we calculate the mean value for the projectile scattering angle $\langle\theta_P\rangle$ as a function of $p_{R\|}$, as well as the simple differential recoil-ion momentum distribution after integration on θ_P.

Equation (3) shows that the longitudinal recoil-ion momentum reaches its threshold $p_{R\|}^{\min} = -v/2 + |\varepsilon_i|/v$ when $\vec{p}_e = \vec{v}$, *i.e.*, at the ECC peak. In the longitudinal recoil-ion momentum distribution, the ECC electrons contribute to a finite cross section [4, 8] at threshold for positive ion while it is null for negative ones (antiproton).

The above formulation does not depend on the particular approximation used for the transition matrix calculation. Two well known theoretical approaches are here examined: the continuum distorted wave-eikonal initial state (CDW-EIS) and the Classical Trajectory Monte Carlo (CTMC). An active electron model is employed for the Helium treatment. In both theories we account for the projectile-residual target interaction with an effective target charge $Z_{eff} = 1.35$.

3. Results

In the upper panel of figure 1, we present theoretical calculations of $\langle\theta_P\rangle$ as a function of $p_{R||}$ for helium ionisation by 50 keV proton and antiproton impact. Although quantitative differences are observed between CDW-EIS and CTMC, both calculations agree in two important features: the mean proton scattering angle decreases as we approach to the threshold and, on the contrary, the mean antiproton scattering angle shows an increase as we get near the threshold. Therefore, based on $\langle\theta_P\rangle$ as a quantitative parameter, we find a projectile focusing (defocusing) of the projectile for positive (negative) ion impact as we approach the $p_{R||}$ threshold.

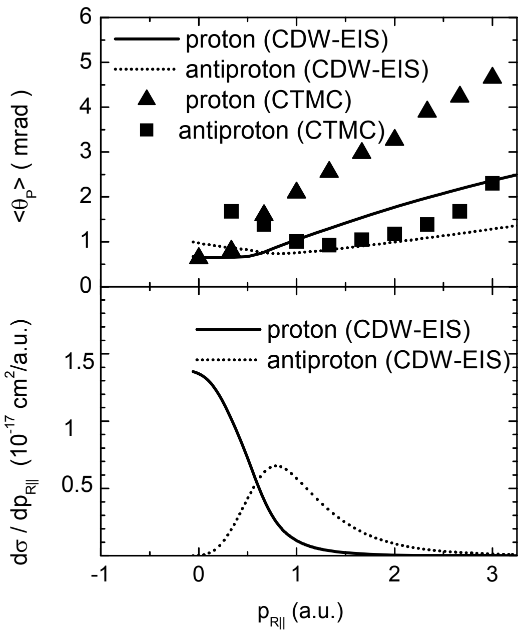

Figure 1. Mean projectile scattering angle and recoil-ion longitudinal momentum distribution as a function of the longitudinal recoil-ion momentum for single ionization of He by 50 keV (v=1.41a.u.) proton (—, ▲) and antiproton (- - -, ■) impact. Curves: CDW-EIS calculation, symbols: CTMC calculation.

In the lower panel, the recoil-ion longitudinal momentum distribution using CDW-EIS is shown. As discussed in [4] this magnitude is quite different for both projectiles. For protons, due to the ECC cusp, the cross sections are finite at threshold while, for antiprotons, the cross section goes to zero.

In order to get a closer view of the differences between proton and antiproton ionization we evaluate the doubly differential cross section $d^2\sigma / d\theta_P \; dp_{R||}$ as a function of θ_P, for fixed values of the recoil-ion longitudinal momentum. As it is shown in figure 2, these DDCS show two main features. First, the projectile distribution peak shifts to lower values of θ_P as we approach the threshold value for proton impact, and to slightly greater values for antiprotons. Second, the width of the distribution shrinks from a broad distribution for $p_{R||} = 3$ a.u. to a sharper one near threshold for proton impact. On the contrary, for antiproton impact the distribution become thicker as one approaches $p_{R||}^{\min}$. It must be noticed that for this particular case we cannot display the distribution too close to $p_{R||}^{\min}$ since it goes to zero at this threshold value. The combined effect of these features accounts for the features shown by the upper panel in figure 1.

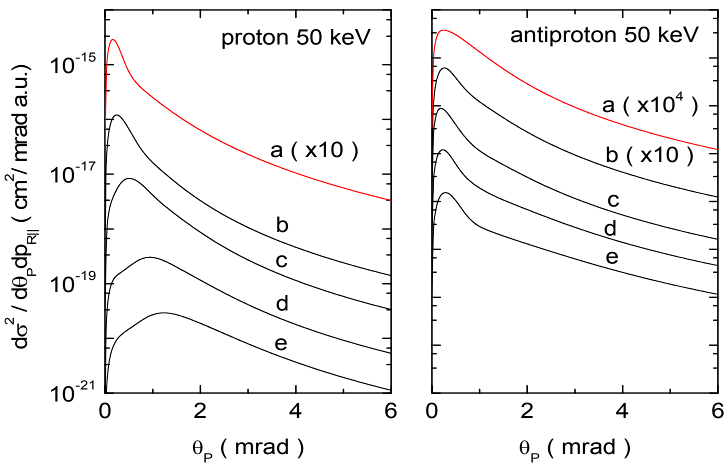

Figure 2. Doubly differential cross section for 50 keV (v=1.41 a.u.) proton (antiproton) impact helium ionization as a function of the transverse transfer momentum for fixed values of the longitudinal recoil-ion momentum $p_{R||}$: (a) 0.08; (b) 0.5; (c) 1; (d) 2 and (e) 3 a.u, respectively.

4. Final Remarks

Based on two well established theoretical methods: CDW-EIS and CTMC, we have provided evidence of different behaviours between proton and antiproton scattering in ionising collisions. This three-body effect differs from a simplistic two-body scattering that predicts no differences. In particular the final-state interaction between the projectile and the electron at ECC appears to be a deciding factor to explain this difference. Experimental work to verify these findings would be welcome.

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