Momentum-transfer dependence of ionization cross sections for C$^{6+}$+He collisions

J Fiol$^1$, S Otranto$^{2,3}$ and R E Olson$^2$

$^1$CONICET and Centro Atómico Bariloche, S C de Bariloche, Río Negro, Argentina
$^2$Physics Department, University of Missouri-Rolla, Rolla, MO 65401, USA.
$^3$CONICET and Dto de Física, Univ. Nac. del Sur, 8000 Bahía Blanca, Argentina.

E-mail: olson@umr.edu

Abstract. In this work we study the dependence of the fully differential cross sections (FDCS) for single ionization of He by 100 MeV/amu C$^{6+}$ on the momentum transferred by the projectile to the target. Three dimensional plots of the FDCS are used to illustrate how the different configurations contribute when the theoretical results are convoluted over the experimental uncertainties. This convolution is shown to be essential in order to properly reproduce the measured data.

1. Introduction

Fully differential cross sections (FDCS) have been available for single ionization in electron-atom collisions for more than three decades [1, 2]. However, only in the last couple of years has a similar level of detail become feasible for collisions by heavy ionic projectiles. The use of heavy ions introduces new degrees of freedom compared to that for electron impact. On the one hand, for positive ions not only are the electron excitation and ionization channels open as for electron collisions, but also the electron-capture channel is available. Moreover, the possibility of varying the projectile charge introduces an additional parameter which by itself determines the collision regime. Increasing the projectile charge at a given velocity makes it possible to move fast collisions into a non-perturbative regime. These additional levels of flexibility cause the collisions by heavy ions to be a much more complex process than in the case of electron impact.

At large incidence velocities, the probability of electron capture is negligible and differences due to different projectile charges can be separately studied. Very recently, a considerable amount of effort has been devoted to the experimental and theoretical determination of fully differential cross sections for ionization of helium by fast highly charged ions (see for instance our previous works [3-6] and the references therein). One main conclusion of previous studies is the surprising result that experiment and theory strongly disagree even in a perturbative collision regime, especially at very large incidence velocities. For instance, the C$^{6+}$+He collision system at 100 MeV/u, corresponding to approximately 58 a.u. of velocity shows strong discrepancies between experiment and calculations of the fully differential cross sections [3,7,8]. However, very recent work concludes that experiment and theory are in good agreement if an accurate description of the experimental momentum uncertainties are incorporated in the calculations before testing them against the data [4-6].

In this communication we investigate the single ionization of helium by C$^{6+}$ at an impact energy of 100 MeV/u. We focus on the dependence of the cross sections on the momentum transferred by the
projectile to the target and discuss how this dependence translates to the observed cross sections after their convolution over the experimental momentum uncertainties.

2. Comparison with experimental data

The quantum mechanical theory employed in this work has been thoroughly documented [8-10]. In this work the electron in both the Born initial state and final Continuum Distorted Wave (CDW) state is described as evolving in a Hartree-Fock potential modeling the field of the He⁺ residual-ion [8,11,12]. The interactions of the projectile with the emitted electron and with the residual-ion are approximated by pure Coulomb potentials.

In order to convolute the theoretical cross sections over the experimental momentum uncertainties, more than $6 \times 10^4$ FDCS had to be calculated. Figure 1 shows the comparison of experimental FDCS with convoluted calculations in three-dimensional plots from [6]. The electron is emitted with energy $E_e=6.5$ eV and the magnitude of the momentum transfer is $Q=0.75$ a.u. The CDW theoretical cross section corresponding to this configuration, shows the familiar double-lobe structure from the so-called binary and recoil peaks as shown in ref. [6]. On the other hand, the experimental data and the convoluted calculations present similar shapes and magnitudes to one another, but differ greatly in the “waist” region of the binary and recoil lobes.

We further note that even a simple First Born Approximation is able to describe the experimental data if the momentum uncertainties are included.

![Figure 1. Theoretical CDW and experimental fully differential cross sections for helium single ionization by impact of 100 MeV/u C⁶⁺. Calculations have been convoluted over the experimental momentum uncertainties on Q [6].](image)

3. Dependence of cross sections with the momentum transfer

In order to understand how the convolution over the momentum resolution changes the observed fully differential cross sections, we present unconvoluted results for other values of the momentum transfer. Figure 2 shows the cross section at the same electron energy ($E_e=6.5$ eV) but with two smaller momentum transfers, $Q=0.10$ and $Q=0.35$ a.u. As can be observed, for smaller momentum transfer, the recoil lobe increases. For $Q=0.10$ a.u. the probability of electron emission is of the same order for both binary and recoil collisions.
In order to give a quantitative idea of the dependence of the cross sections on Q, in figure 3 we display the in-plane cross sections as a function of the polar emission angle. Since the magnitude of the fully differential cross sections increase for the lower Q values, we have multiplied these cross sections by Q in order to show all the curves in the same plot. For momentum transfers Q=0.15, 0.25, 0.40 and 0.75 a.u. the same trends observed in the three-dimensional plots can be appreciated. The magnitude of the cross sections sharply decreases with increasing momentum transfer and the recoil peak increases for the smaller Q-values.

The convolution over the momentum uncertainties must be performed in three dimensions. For each value of “nominal” momentum transfer that lies in a given plane, contributions from smaller and larger values of Q in the same plane and also processes where Q lies outside such plane have to be considered. Since the cross sections evaluated in the scattering plane are larger than those outside this plane, the convolution mainly modifies the recoil peak leaving the binary peak unchanged. Outside the scattering plane, on the other hand, contributions arising from small momentum transfers strongly modify the shape and intensity of the angular spectra [4-6].

4. Conclusions
We have performed calculations of fully differential cross sections within a CDW theory with a Hartree-Fock description of the initial and final states for the active electron. We have investigated the dependence of the fully differential cross sections on the momentum transferred by the C\textsuperscript{6+} projectile to the He target. The sharp increase in magnitude of the cross sections for decreasing values of Q is the reason why small uncertainties in the momentum resolution produce large distortions on the observed angular distributions. Hence, the observed cross sections are strongly modified by the convolution of processes corresponding to different values of the Q vector.
Figure 3. Differential cross sections in the scattering plane, which is defined by the incident velocity \( v \) and the momentum transfer \( Q \). The emitted electron energy is \( E_e = 6.5 \) eV.

Acknowledgment
Support by the Office of Fusion Energy Sciences, DOE and by Agencia Nacional de Promoción Científica y Tecnológica (ANPCyT, Argentina) under PICT 03-14399 is gratefully acknowledged.

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