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Abstract. We present theoretical and experimental results for angular and energy distributions of electrons emitted in collisions of B2+ with He atoms. In particular, we analyze the cusp formed by projectile Electron Loss to Continuum (ELC) and Electron Capture to Continuum (ECC). The cusp shape dependence on the electronic initial state is discussed and compared with our previous measurements on Li+ + He.

The projectile incident energy was about 414 keV/u and the electron detection angle was varied between 0° and 150°. The experimental data is compared with three-body quantum Continuum-Distorted-Wave calculations.

1. Introduction
Electron emission produced by collisions has been studied for decades in order to understand fundamental atomic processes. Of particular interest here are one- and many-electron processes induced by interactions between two partially screened nuclei and their bound electrons. We studied collision systems where the binding energy of the projectile electrons is similar to the binding energy of the target electrons, thus projectile as well as target electrons can no longer be considered as passive (frozen in their orbitals during the reaction). Therefore, target and projectile, and even simultaneous ionisation can give a noticeable contribution to electron emission.

The studies of projectile ionisation (stripping) have also important applications in design parameters for ion accelerators, for the energy loss (range) of ions in matter, and for limiting beam transport losses as well as losses in storage rings. At present, scaling laws, applicable to a wide range of systems, are the best way of extrapolate data [1–5], specially for many-electron collision systems where multiple-electron processes can dominate the observed spectra and one-electron theories are inadequate.

In this work we present experimental angular and energy distributions of electrons emitted in collisions of B2+ with He atoms and the corresponding theoretical results of quantum three-body CDW calculations. In particular, data taken at zero degrees for energies in the region of the cusp, formed by projectile Electron Loss to Continuum (ELC) and Electron Capture to Continuum (ECC), are compared with measured data for Li+ + He at very similar collision energies.
2. The experimental arrangement
Experimental data were measured at the 1.7 MV Tandem accelerator at Centro Atómico Bariloche. The experimental set-up is described in detail elsewhere [6], thus only details related to the present experiment are reported here. Boron ion beams emerging from the accelerator with approximately 414 keV/u are collimated in the transport section by two sets of four collimators to 0.60×0.60 mm², determining a beam divergence of 0.7 mrad (half-angle). Inside the collision chamber the projectiles collide with the effusive target at the focus of a cylindrical mirror spectrometer. The analyzer rotates in a plane perpendicular to the gas flow direction, so it measures energy distributions of the electrons emitted in the collision for any selected angle between 0 and 180 degrees. After the collision region, the beam is collected in a Faraday cup. The collected charge is used to normalize the electronic distributions to a constant number of projectiles.

3. Theory
The experimental data have been compared to quantum three-body CDW calculations. The theoretical model has previously been used by the authors to describe electron emission in Li⁷⁺ (q = 1, 2) [7] and Al⁹⁺ (q = 1, 2, 3) collisions with He targets [8]. The initial-channel distorted wavefunction is written as the product of an initial target bound state, and a Coulomb continuum factor that describes the interaction between the target active electron and the projectile in the entry channel. After the ionisation, the electron evolves in the combined fields of the projectile and the residual target. The final-channel distorted wavefunction is chosen as a target continuum state multiplied by a Coulomb continuum factor. In order to extend this model to the case of dressed projectiles [9], the projectile potential was represented by means of parametric Green-Sellin-Zachor (GSZ) potentials [10].

To estimate the contributions of simultaneous ionisation from the target and the projectile a probabilistic approach was used. It is obtained as the sum of the differential cross sections for projectile ionisation due to the interaction with a He target, and for He target ionisation by B²⁺ impact, each of them weighted by their corresponding total cross sections (see [7, 8]). This approach gives a rough estimate of the contribution by simultaneous ionisation, and does not take into account any interference effects. It is expected to be more suitable when electrons in one center are much more deeply bound than in the other center.

4. Results and Discussions
Doubly differential cross sections (DDCS) for electron emission in collisions between B²⁺ projectiles and He targets were measured. Figure 1 shows the experimental electron distributions at different emission angles for 4.5 MeV B²⁺ ions impinging on He. At 0 degrees the cusp at around 226 eV is most pronounced and its intensity decreases with increasing angle. These electrons are ejected into a small cone of half angle about 5° in the forward direction with a velocity that matches the velocity of the incident ions. At larger angles the so-called Binary-Encounter Peak (BEP) appears at higher electron energies, whose maximum shifts to lower energies with increasing angles.

At large emission angles (backward directions) a small bump is observed at energies of about 35 eV. This is the signature of autoionisation processes for the doubly excited state of Helium. At lower angles this mechanism is hidden in the background produced by other direct ionisation mechanisms. A similar structure, but associated with B²⁺ autoionisation, is shown for electron emission in the forward direction at electron energies of 740 eV [11].

Electrons with laboratory velocities close to the beam velocity are produced in three major processes. (i) Projectile electrons are ionized to continuum states of low momentum with respect to the projectile nucleus (ELC). (ii) Electrons are transferred from a bound state of the target nucleus to a low-lying continuum state of the projectile nucleus (ECC). (iii) Electrons from projectile Auger processes appear near the projectile velocity in the laboratory frame. However, in the experimental spectra we do not observe any of these autoionisation lines from the Li-like B ions in the main peak.
The energy distribution of electrons ejected at 0° cusp are compared in Figure 2 with the predictions of the CDW model. Just for comparison reasons the experimental data were normalized to agree with the theory at an energy of 400 eV. A good overall agreement is observed, with marked differences only on the ECC cusp, where the experimental angular and energy finite resolutions smooth the $1/v$ behaviour.

The calculations allow us to distinguish between the different contributions to the differential electron emission cross section. In the neighborhood of the cusp the major contribution comes from electrons emitted from the projectile (ELC). It is observed that both projectile ionisation and simultaneous ionisation contribute similarly to the ELC cusp, and the corresponding cross-sections have similar shapes. We separate the contributions to projectile ionisation due to the 2s electron from the 1s electrons of the Li-like B ion. In the cusp, the 2s ionisation dominates but in the high energy end, above 700 eV, 1s ionisation takes over. However, this effect is completely hidden in the total emission cross-section because target ionisation becomes strongly dominating above 400 eV. The difference in the cusp by ionisation of the 2s electron from the 1s electron ionisation can be seen when comparing the Li-like B ion with the data taken for He-like Li ions (see Figure 3) [7]. In the cusp from B$^{2+}$, the 2s ionisation is dominant, whereas for Li$^+$ it is only 1s ionisation. Contributions from a possible metastable He-like Li was found to be negligible. The cusp for B$^{2+}$ is significantly wider than for Li$^+$ projectiles, even when the binding energies of the 1s electron in Li$^+$ (first ionisation potential, 76 eV) almost doubles the one of 2s electrons in B$^{2+}$ (38 eV).

In Figure 4 we compare the experimental spectra with predictions from the CDW model for four different emission angles, 10, 30, 90, and 150 degrees. The data were normalized using the same factor as in figure 1. The overall agreement for emission close to the direction of incidence is quite good. However, for out-of-axis emission the theory overestimates the measured data, and the agreement only improves again for very large angles (150°).

When we analyse the contributions from the different processes: projectile, target and simultaneous
Figure 2. Theoretical and experimental DDCS in the same condition as in Figure 1, for $0^\circ$ emission angle. The absolute value of the experimental results has been scaled to those of the CDW theory at 400 eV. Full line, total electron emission; dashed line, target ionisation; dotted line, projectile ionisation; dash-dotted line, simultaneous ionisation. The dot-dot-dash line is the contribution to projectile ionisation from the $2^+ (1s2)$ orbital, while short-dashed line is the contribution from the $2^+ (2s1)$ orbital.

Figure 3. DDCS for electron emission in collision between 414 keV/u ($v_p \approx 4.08$ au) $2^+\text{B}$ and 440 keV/u ($v_p \approx 4.20$ au) $2^+\text{Li}$ with He targets for a fixed $0^\circ$ emission angle. The cusp top has been normalized to a value of one, and the energy axis has been scaled to the incident energy $E_0$ for better comparison.
ionisations, we see that the main reason for the discrepancies with the experiment at intermediate angles arises from overestimation of target emission. On the other hand, in the vicinity of the incident velocity, at forward angles, the theoretical values for processes associated with electron projectile emission (projectile and simultaneous ionisation) are slightly overestimated, giving a more pronounced maximum than the experimentally observed.

**Figure 4.** Experimental and theoretical DDCS for electron emission in collisions of 414 keV/u B$^{2+}$ on He. Corresponding emission angles are, a) $\theta = 10^\circ$, b) $\theta = 30^\circ$, c) $\theta = 90^\circ$, and d) $\theta = 150^\circ$.

### 5. Conclusions

Double differential cross-sections for electron emission in B$^{2+} +$ He collisions were experimentally determined. The measured data has been compared to previous measurements on Li$^+ +$ He collisions and to quantum-mechanical CDW calculations. By comparing the observed data with the theoretical results, the relative importance of the different processes contributing to the total electron emission has been analysed. Present results show that target ionisation dominates the spectra for all energies and angles emissions, except in the vicinity of the incident velocity (the ELC region). The main contributions of electrons emitted in the ELC region arise from electrons emitted from the projectile, either in pure projectile-ionisation or simultaneous-ionisation processes.

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