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Experimental and theoretical results on electron emission in collisions between partially dressed ions with He targets

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Abstract
Experimental and theoretical results for electron emission in 440 keV u^{-1} Li^+ with He targets are presented. Theoretical cross-sections are obtained using extensions of the continuum distorted wave and the continuum distorted wave-eikonal initial state models to the case of dressed projectiles and a four-body classical trajectory Monte-Carlo. The contributions of electron emission from the different aggregates of the collision system are investigated.

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(Some figures may appear in colour only in the online journal)

1. Introduction

When considering dressed projectiles, the process of target ionization can be significantly affected by the projectile electronic distribution. Therefore, other electron production mechanisms besides target ionization can occur, and new features in the electron spectra may appear [1]. The effects of the projectile electrons on the target ionization were first studied by Bates and Griffing [2], and experimental spectra for ionization by partially dressed projectiles at large energies have been interpreted as arising from two different contributions termed monoelectronic interaction (screening) and dielectronic interaction (antiscreening) [3, 4] (see also [5] and references therein). This dielectronic process is visible after a certain threshold of the projectile incident velocity, when the kinetic energy of the projectile electron is larger than the binding energy of the target [6]. At lower impact energies there is no clear-cut separation of monoelectronic and dielectronic effects. Hence, the spectral structures appearing from the different electron-production mechanisms can be studied individually when fast projectiles are used in the experiments.

In this work, we present experimental and theoretical results for electron emission in collisions of Li^+ with He atoms at an impact energy of 440 keV u^{-1}.

2. Experimental setup and procedure

Energy distributions of electrons emitted in collisions of Li^+ with He were measured for 440 keV u^{-1} incident energy. The ion beam generated in the new 1.7 MV tandem accelerator at Centro Atómico Bariloche intersects the effusive He target at the focus of a cylindrical mirror analyzer [7]. The electrons emitted, analyzed in energy and angle, were detected with an electron-multiplier detector. For all measurements in this work, the angular acceptance was set to 2° and the energy resolution was 6%. After the collision, the projectiles were collected in a Faraday cup at the end of the line

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to normalize the electron distributions to the number of impinging projectiles.

Doubly differential cross-sections (DDCS) for electron emission were determined for several energies and angles ranging from 0 to 170° relative to the incident beam direction. Data have been normalized to total cross-sections by comparison with the experimental data reported by Shah and Gilbody [8] and Woitke *et al* [9].

3. Theory

The experimental data have been compared with theoretical cross-sections calculated with the classical trajectory Monte-Carlo (CTMC) [10] and two quantum-mechanical distorted wave models, namely the continuum distorted wave (CDW) [11] and the continuum distorted wave-eikonal initial state (CDW-EIS) [12].

3.1. Distorted wave models

We have computed electron emission by means of extensions of the CDW and CDW-EIS models to the case of dressed projectiles, following the philosophy of the previously introduced work on target ionization [13, 14]. In such extensions the projectile potential V_{P} was represented by means of two-parameter Green–Sellin–Zachor potentials [15], usually called GSZ potentials. These potentials can be written as a short-range term plus a long-range term, the latter due to the asymptotic screened projectile charge q

$$V_{\mathrm{P}}(s) = V_{\mathrm{P}}^{\mathrm{sr}}(s) + V_{\mathrm{P}}^{\mathrm{lr}}(s), \tag{1}$$

$$V_{\mathrm{P}}^{\mathrm{sr}}(s) = -\frac{1}{s}(Z_P - q)\left[H(\mathrm{e}^{s/d} - 1) + 1\right]^{-1}, \tag{2}$$

$$V_{\mathrm{P}}^{\mathrm{lr}}(s) = -\frac{q}{s} \tag{3}$$

with s being the distance of the target active electron to the projectile nucleus, and H and d, adjustable parameters. Therefore, with this choice for the projectile potential, the transition amplitude as a function of the impact parameter $\vec{\rho}$ is

$$\mathcal{A}_{if}(\vec{\rho}) = \mathcal{A}_{if}^{\mathrm{sr}}(\vec{\rho}) + \mathcal{A}_{if}^{\mathrm{lr}}(\vec{\rho}), \tag{4}$$

where $\mathcal{A}_{if}^{\mathrm{lr}}$ is the well-known transition amplitude for a bare ion of charge q [11, 12], and $\mathcal{A}_{if}^{\mathrm{sr}}$ is a term related to the short-range term of the potential V_{P} (see [14]). This separation of the transition amplitude is completely general, in principle, whenever the projectile potential can be separated into short- and long-range contributions.

The DDCS as a function of electron energy and emission angle for projectile ionization are obtained transforming the kinematic quantities from the projectile to the laboratory rest frame by means of the well-known expression

$$\frac{\mathrm{d}\sigma(\theta, \varepsilon)}{\mathrm{d}\Omega\,\mathrm{d}\varepsilon} = \left(\frac{\varepsilon}{\varepsilon'}\right)^{1/2} \frac{\mathrm{d}\sigma'(\theta', \varepsilon')}{\mathrm{d}\Omega'\,\mathrm{d}\varepsilon'}, \tag{5}$$

where the primed (unprimed) quantities are associated with the projectile (laboratory) rest frame (see e.g. [5]).

In order to estimate the contribution of simultaneous ionization from the target and the projectile (dielectronic ionization), a probabilistic approach was used. If we consider the collision of a generic projectile A^{q+} with a He target, the DDCS for simultaneous ionization was calculated as

$$\mathrm{DDCS}^{(\mathrm{sim})} = \frac{\mathrm{DDCS}^{(a)}\mathrm{TCS}^{(a)}}{\mathrm{TCS}^{(a)} + \mathrm{TCS}^{(b)}} + \frac{\mathrm{DDCS}^{(b)}\mathrm{TCS}^{(b)}}{\mathrm{TCS}^{(a)} + \mathrm{TCS}^{(b)}}, \tag{6}$$

where $\mathrm{DDCS}^{(a)}$ represents the ionization of the projectile A^{q+} interacting with a He^{+} target, $\mathrm{DDCS}^{(b)}$ the ionization of the He target by $\mathrm{A}^{(q+1)+}$ impact, $\mathrm{TCS}^{(a)}$ the ionization total cross-section of He by A^{q+} impact and $\mathrm{TCS}^{(b)}$ the ionization total cross-section of the projectile A^{q+} interacting with a He target. This approach can give a rough estimation of the simultaneous ionization contribution and does not take into account any interference effects.

3.2. Classical trajectory Monte-Carlo model

The nCTMC method used in this work has been developed and thoroughly described previously [16]. This version of the classical model has been very successful in the description of multiple-ionization processes and is especially well suited for analyzing collision systems with electrons in more than one center, such as those in the present work [17]. Here a four-body system has been solved with each center described as an one-electron atom, where the effects of the remaining electrons are included as a screening to the Coulomb nuclear potential. The model potentials for both the projectile and target *frozen* cores were represented by the two-parameter GSZ potentials [15], similar to those used in the distorted wave models (see above). In this model the electrons both in the target and in the projectile are perturbed by both the nucleus and the electron in the opposite center. Thus, all relevant ionizing interactions were explicitly included in this model.

4. Results and conclusions

In figures 1 and 2 experimental and theoretical DDCS for electron emission in collisions between 440 keV u^{-1} Li^{+} and He atoms are presented as a function of the electron energy for a fixed emission angle of 30° and 150°, respectively.

In both cases the CDW-EIS model shows good agreement with experimental data, and the CDW one shows some overestimation for 30° emission angle but shows good agreement for 150° emission angle. However, the comparison between experiments and the distorted wave models should be taken with care given the way the simultaneous ionization was treated. As mentioned above, we have made a rough estimation of the contribution of the simultaneous ionization to the electron emission. A two-electron approach should be developed in the future for the correct treatment of this process. CTMC results are in good agreement for low energy regions, showing overestimation at electron energies larger than 600 eV for 30° and 100 eV for 150° emission angle. For 150° emission angle, for larger electron energies, the change of slope in the experiments is well represented by the CDW and CDW-EIS models and it clearly shows that it is mainly

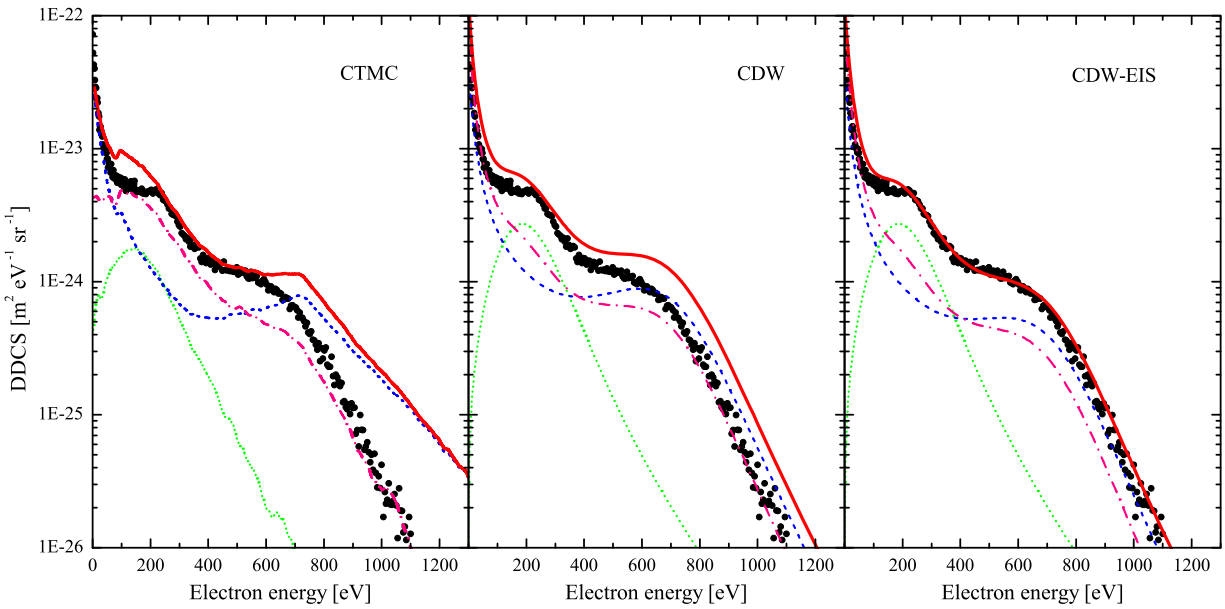

Figure 1. Doubly differential cross-section for electron emission in collisions of 440 keV u^{-1} Li$^+$ with He as a function of electron energy for 30° fixed ejection angle. •, experiment; · · · · · ·, projectile ionization; - - - -, target ionization; — · —, simultaneous ionization; ——, total ionization.

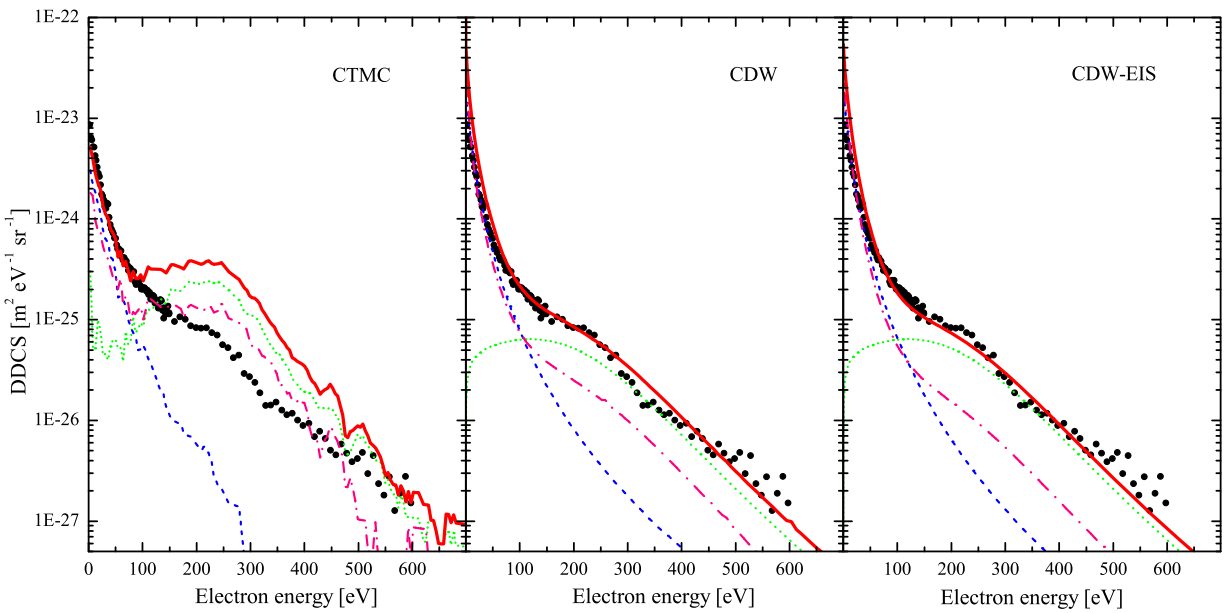

Figure 2. The same as figure 1 but for 150° fixed emission angle. •, experiment; · · · · · ·, projectile ionization; - - - -, target ionization; — · —, simultaneous ionization; ——, total ionization.

due to the contribution of projectile ionization followed in importance by simultaneous ionization. The target ionization gives a contribution similar to that of the simultaneous ionization at low electron energies but rapidly falls after 100 eV.

In conclusion, the CDW and CDW-EIS models extended to dressed projectiles together with a classical CTMC calculations were applied to the case of 440 keV u^{-1} Li$^+$ + He. Experimental results were also obtained for a wide variety of angles and other collision systems, namely 440 keV u^{-1} Li^{q+} + He ($q = 1, 2$) and 100–200 keV u^{-1} Al^{q+} + He ($q = 1, 2, 3$). These results with the corresponding theoretical calculations are to be published in a forthcoming paper.

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