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2011 Phys. Scr. 2011 014027

(http://iopscience.iop.org/1402-4896/2011/T144/014027)

Phys. Scr. **T144** (2011) 014027 (3pp) doi:10.1088/0031-8949/2011/T144/014027

Quantum interferences in single ionization of He by highly charged dressed-ions impact

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Received 28 January 2011
Accepted for publication 28 January 2011
Published 20 June 2011
Online at stacks.iop.org/PhysScr/T144/014027

Abstract
Ionization of He targets by impact of partially stripped ions is investigated by means of an extension to the continuum distorted wave-eikonal initial state model with a particular representation of the projectile potential. Structures appearing superimposed on the binary encounter peak are interpreted in terms of coherent interference of short- and long-range contributions of the perturbative projectile potential. The case of 600 keV u^{-1} Au^{11+} ions impinging on He is presented and discussed.

PACS number: 34.50.Fa

(Some figures in this article are in colour only in the electronic version.)

1. Introduction

For over two decades the continuum distorted wave-eikonal initial state (CDW-EIS) model [1] has been shown to be a reliable method to calculate the single ionization differential and total cross sections for different projectile/target combinations from intermediate to high non-relativistic impact energies. However, some experimental results can still not be fully described with existing theories. This was the case in the results obtained by Schmidt–Böcking's group [2] for electron emission spectra as a function of electron energy, at fixed emission angles, in the region of the binary encounter peak for 1 MeV u^{-1} U^{21+} impinging on He. The spectra presented structures superimposed on the peak. Reinhold *et al* [2], (see also [3]), using a combination of quantum-mechanical and classical descriptions, showed that these structures were due to quantum effects in the elastic differential cross section for the scattering of the ionized target electron with the impinging clothed ion. In a previous work [4], we extended the CDW-EIS model to consider dressed-ion impact on He with a particular representation of the projectile potential as given by Green *et al* [5]. These analytical potentials can be separated into a short-range contribution and a long-range Coulomb potential due to the asymptotic screened projectile charge. This theoretical method was applied with success to describe the U^{21+}+ He spectrum [4]. The structures in the doubly differential cross sections (DDCS) were explained as interference between short- and long-range amplitudes. In the present work we apply our model to single ionization of He by impact of 600 keV u^{-1} Au^{11+} ions. For this case, the experimental results obtained by Wolff *et al* [6] cover a large range of electron energy and emission angles and show similar interference effects as those found for U^{21+}. The theoretical results show good qualitative agreement with the experiments.

2. Theory

Let us consider the process of single ionization of helium by impact of a fast partially stripped ion of nuclear charge Z_P and degree of ionization q:

$$Z_P^{q+} + \mathrm{He} \longrightarrow Z_P^{q+} + \mathrm{He}^+ + e^-.$$

The one-active electron reaction Hamiltonian is

$$H_a = -\frac{\nabla_x^2}{2} + V_T(\vec{x}) + V_P(\vec{s}) + \frac{Z_P Z_T}{R}, \qquad (1)$$

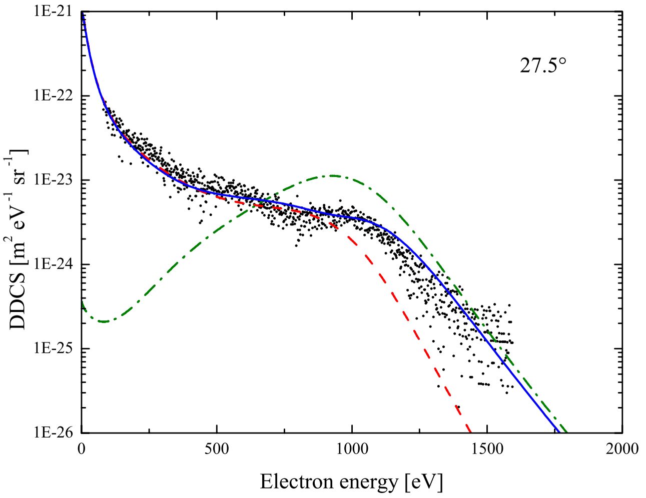

Figure 1. Double differential cross section for single ionization of He by 600 keV u^{-1} Au^{11+} impact as a function of electron energy for a fixed 27.5° emission angle. Theory: ——, present CDW-EIS calculations; - - - -, present CDW-EIS calculations considering only the long-range contribution of the projectile potential; — · —, present CDW-EIS calculations considering only the short-range contribution of the projectile potential. Experimental data: • (taken from [6]).

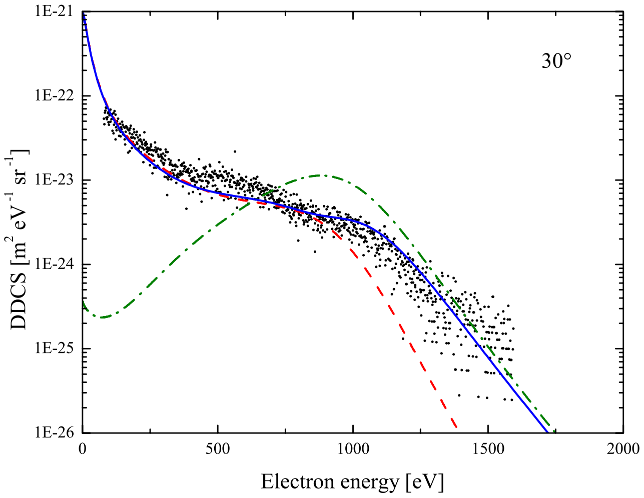

Figure 2. Same as figure 1 but for a fixed 30° emission angle.

where $\vec{x}$ ($\vec{s}$) represents the active electron position vector from a reference frame fixed to the target (projectile) nucleus, Z_T is the target nuclear charge ($Z_T = 2$ in the case of helium), V_T and V_P are the target and projectile potentials felt by the active electron and $\vec{R}$ is the internuclear vector. We will employ the straight-line version of the impact parameter approximation where the internuclear vector is given by $\vec{R} = \vec{\rho} + t\vec{v}$, with $\vec{\rho}$ the impact parameter, $\vec{v}$ the impact velocity and t the collision time, taking $t = 0$ at the nearest distance between the nuclei.

We have chosen a particular representation of the projectile potential V_P as given by Green *et al* [5], usually called GSZ potentials. These potentials can be written as a short-range term plus a long-range term due to the asymptotic screened projectile charge q:

$$V_P(s) = V_P^{sr}(s) + V_P^{lr}(s), \tag{2}$$

where

$$V_P^{sr}(s) = -\frac{1}{s}(Z_P - q)\left[H(e^{s/d} - 1) + 1\right]^{-1}, \tag{3}$$

$$V_P^{lr}(s) = -\frac{q}{s}, \tag{4}$$

with adjustable parameters H and d. In the CDW-EIS model, the initial and final states are chosen to verify correct asymptotic conditions for the Coulomb potential. For the present case and in this spirit, we chose initial and final distorted wavefunctions that verify the boundary condition corresponding to the asymptotic projectile charge:

$$\chi_i^+(\vec{x}, t) = \Phi_i(\vec{x}, t)\mathcal{L}_i^+(\vec{s}), \tag{5}$$

$$\chi_f^-(\vec{x}, t) = \Phi_f(\vec{x}, t)\mathcal{L}_f^-(\vec{s}), \tag{6}$$

with

$$\mathcal{L}_i^+(\vec{s}) = \exp\left[-i\nu \ln(vs + \vec{v} \cdot \vec{s})\right], \tag{7}$$

$$\mathcal{L}_f^-(\vec{s}) = N^*(\zeta)\, {}_1F_1\left(-i\zeta; 1; -i(ps + \vec{p} \cdot \vec{s})\right), \tag{8}$$

where $\vec{p}$ is the ejected electron momentum in the projectile reference frame, $\nu = q/v$, $\zeta = q/p$, ${}_1F_1$ is the confluent hypergeometric function, and N is the normalization factor of the hypergeometric function. The functions Φ_i and Φ_f are the target initial and final wavefunctions as given in [1].

With this choice for the V_P potential, the scattering amplitude as a function of the impact parameter results in

$$\mathcal{A}_{if}(\vec{\rho}) = \mathcal{A}_{if}^{sr}(\vec{\rho}) + \mathcal{A}_{if}^{lr}(\vec{\rho}), \tag{9}$$

where $\mathcal{A}_{if}^{lr}$ is the well-known transition amplitude in the CDW-EIS model for a bare ion of charge q (see [1]) and $\mathcal{A}_{if}^{sr}$ is a new term that has to do with the short-range term of the potential V_P. This separation of the transition amplitude is completely general in principle whenever the projectile potential can be separated into short- and long-range contributions. Here we have calculated the short-range part for the particular case of GSZ potentials.

3. Results and discussion

In a previous work [4] we have applied this extension of the CDW-EIS model to the case of single ionization of He by 1 MeV u^{-1} U^{21+} impact, showing very good qualitative agreement between the theoretical results and the experimental data. Now we apply the extension to the case of single ionization of He by 600 keV u^{-1} Au^{11+} impact. For this system, there are experimental data from Wolff *et al* [6] showing structures in the binary encounter peak in the DDCS as a function of electron energy for a fixed emission angle in the angular region between 22.5° and 32.5°.

In figures 1 and 2, we present the DDCS as a function of electron energy for a fixed emission angle of 27.5° and 30°, respectively. In the figures we include the experimental data of Wolff *et al* [6] normalized to the theoretical results at 100 eV for a 27.5° emission angle. We note that there is good qualitative agreement between the theoretical results and the experimental data. The experimental data show a double peak structure that is reproduced by the theory. In the figures we also include the contributions of amplitudes corresponding to the short- and long-range terms of the potential separately. This shows that for low emission energies the dominant contribution is that of the long-range part of the potential; on the contrary, for higher electron energies the larger contribution is that of the short-range part of the potential. For intermediate energies, the CDW-EIS total DDCS in the binary encounter region appears situated between short- and long-range predictions, as a clear signature of the presence of interference, which also leads to the smooth structures found superimposed in the binary encounter peak.

4. Conclusions

In conclusion, we have applied the extension made to the CDW-EIS model for the case of clothed ions employing Green's [5] form for the projectile potential to the case of single ionization of He by 600 keV $u^{-1}Au^{11+}$ impact. Good qualitative agreement is found with the available experimental data. More details and results have been presented at the conference.

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