Journal of Electron Spectroscopy and Related Phenomena 192 (2014) 19–25

Contents lists available at ScienceDirect

Journal of Electron Spectroscopy and Related Phenomena

journal homepage: www.elsevier.com/locate/elspec

Low-energy electron-helium scattering in a Nd–YAG laser field

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ARTICLE INFO

Article history:
Received 7 October 2013
Received in revised form
17 December 2013
Accepted 23 December 2013
Available online 10 January 2014

Keywords:
Electron-impact excitation
Low collision energy
Second-order Born approximation
Differential cross sections
Sturmian basis expansion

ABSTRACT

We study the electron-impact excitation of atomic helium, in the presence of a linearly polarized Nd–YAG laser field, accompanied by the transfer of ℓ photons, for low collision energy of 25 eV and laser intensity of 5.3×10^{11} W cm^{-2}. The second-order Born approximation has been used to calculate the differential cross sections. Detailed calculations of the scattering amplitudes are performed by using the Sturmian basis expansion. A detailed analysis is made of the excitation of the $1^1S \rightarrow 2^1S$ and $1^1S \rightarrow 2^1P$ transitions. We discuss the behavior and the variation of the cross sections corresponding to the excitation process for various geometrical configurations.

1. Introduction

The study of electron–atom collisions in the presence of a laser field continue to attract a great deal of attention, not only because of the importance of these processes in applied areas such as plasma heating [1,2], but also in view of their interest in fundamental atomic collision theory. There has been a multitude of theoretical treatments of these processes, most studies of low-energy laser-assisted electron–atom scattering have concentrated on free–free transitions [3–6].

A theoretical model that has been widely compared with is the Kroll–Watson approximation (KWA) [7], in which quantum-mechanical scattering theory is applied to an electron in an electromagnetic field. It is particularly appealing since it has a simple analytical form which relates the free–free cross section, for absorption or emission of n photons, to the field-free elastic-scattering cross section. A generalization of the Kroll–Watson's low frequency approximation to laser-assisted electron impact excitation has been derived by Mittleman [8]. The main assumption of the KWA is that the laser atom interaction can be neglected; that is, the sole purpose of the presence of the atom is to allow the conservation of both energy and momentum during the absorption or emission of the n photons by the electron. The low-frequency requirement is that the incident electron energy be much larger than the photon energy. This approximation has been subsequently examined by a number of authors [9–14]. A particular feature of the KWA is that when the projectile momentum transfer becomes perpendicular to the polarization vector of the laser field, the approximation leading to the derivation of the KWA breaks down [7].

There is still much interest in the applicability of the KWA. A very recent study [15] compared a KWA calculation with a sophisticated R-matrix Floquet calculation of electron-helium excitation in the presence of a CO_2 laser field at scattering energies between 19 and 21.5 eV and laser intensities of 10^7 and 10^8 W cm^{-2}. The two calculations were in excellent agreement, while agreement with experiment is reasonable. Electron-helium excitation from the ground state into the triplet states in a Nd–YAG laser has been treated by Terao-Dunseath et al. [16] in the energy range from 0.65 to 0.78 hartree at intensity of $I = 10^{10}$ W cm^{-2} using the R-matrix Floquet method. Almost all theoretical investigations of the KWA to date have been carried out for free-free cross sections and with 0.117 eV photons. In this paper, we present the results of our calculation on electron-impact excitation of helium for low incident energy of 25 eV, and for laser intensity of 5.3×10^{11} W cm^{-2}, in the presence of 1.17 eV photons from a pulsed Nd–YAG laser. Thus, our calculations lie in a region expected to be well described by Kroll–Watson approximation. This work follows our previous study on laser-assisted elastic collisions in the second Born approximation [17]. Our results show qualitative differences compared to the case of elastic collisions.

In earlier theoretical treatment, the electron–atom collisional state was treated within the framework of the first Born approximation which has the advantage of leading to a simplified analysis, but is only valid at higher projectile energies [18]. Thus we present

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http://dx.doi.org/10.1016/j.elspec.2013.12.016

an alternative approach based on the inclusion of the second-order Born contributions in the treatment of the collisional stage in laser-assisted electron–atom collisions. We have considered the case of excitation process, accompanied by the transfer of a number of photons. Our model includes a perturbative treatment of the dressing of the relevant atomic states which is valid at the moderate laser intensities considered here, so that the laser-target interaction is treated by using a first-order time-dependant perturbation theory. It should be noted that our approach is much less demanding in terms of computational power than the above-mentioned sophisticated R-matrix Floquet treatment. In addition, we obtain interesting results concerning the relative importance of the contributions of the second order Born terms as compared with the first order ones. The paper is structured as follows. In Section 2 we deliver the theoretical treatment of laser-assisted inelastic electron–atom collisions. An account is then given of the techniques we have used to evaluate the scattering amplitudes. Section 3 contains details of our numerical results as well as their physical interpretation and interest. Finally, Section 4 is devoted to conclusion. Unless otherwise stated atomic units (au) are used throughout.

2. Theory

In the presence of the laser field, we consider the electron-helium excitation process represented by the following equation

$$\mathrm{He}(1^1S) + e^-(E_{k_i}, \mathbf{k}_i) + \ell\hbar\omega \longrightarrow \mathrm{He}^* + e^-(E_{k_f}, \mathbf{k}_f), \quad (1)$$

where $\mathbf{k}_i$ and $\mathbf{k}_f$ are respectively the momentum of the incident and scattered electrons in the presence of the laser field. $E_{k_i} = k_i^2/2$ and $E_{k_f} = k_f^2/2$ are the initial and final projectile kinetic energies. The helium target is initially in the ground state 1^1S and will be excited after the collision in one of the final states. The integer ℓ is the number of photons transferred between the electron-target system and the laser field, where positive values of ℓ correspond to the absorption of photons by the system and negative ones to the stimulated emission of photons.

The energy conservation relation corresponding to the laser-assisted inelastic collisions reads

$$E_{k_i} + E_i + \ell\hbar\omega = E_{k_f} + E_f, \quad (2)$$

where E_i and E_f are, respectively, the ground and final exited state energies of the helium target.

We shall assume that the laser field is treated classically as a single mode, spatially homogenous, monochromatic, linearly polarized electric field

$$\boldsymbol{\varepsilon}(t) = \boldsymbol{\varepsilon}_0 \sin(\omega t), \quad (3)$$

$\boldsymbol{\varepsilon}_0$ and ω are the electric field amplitude vector and the laser angular frequency, respectively. The corresponding vector potential is $\mathbf{A}(t) = \mathbf{A}_0 \cos(\omega t)$ with $\mathbf{A}_0 = c\,\boldsymbol{\varepsilon}_0/\omega$.

For the motion of a free electron in the field we have, in the Coulomb gauge, the non-relativistic Volkov wavefunction [19]

$$\chi_k(\mathbf{r}_0, t) = (2\pi)^{-\frac{3}{2}} \exp\left\{ i(\mathbf{k}.\mathbf{r}_0 - E_k t - \mathbf{k}.\boldsymbol{\alpha}_0 \sin(\omega t)) \right\}, \quad (4)$$

where $\mathbf{k}$ denotes the electron wavevector, $E_k = k^2/2$ is its kinetic energy and $\boldsymbol{\alpha}_0 = (\boldsymbol{\varepsilon}_0)/(\omega^2)$ represents the oscillation amplitude of a classical electron in a laser field.

The dressed states of the target atom embedded in the laser field are obtained by solving the Schrödinger equation in the first-order, time-dependent perturbation theory. The dressed wavefunctions are given by [20]

$$\phi_n(\mathbf{X}, t) = e^{-i\mathbf{a}.\mathbf{R}} e^{-iE_n t} \left[\psi_n(\mathbf{X}) + \frac{i}{2} \sum_{n'} \left(\frac{M^-_{n'n} e^{i\omega t}}{\omega_{n'n} + \omega} - \frac{M^+_{n'n} e^{-i\omega t}}{\omega_{n'n} - \omega} \right) \psi_{n'}(\mathbf{X}) \right], \quad (5)$$

where $\mathbf{a}(t) = \mathbf{A}(t)/c$, $\mathbf{R} = \mathbf{r}_1 + \mathbf{r}_2$, $\psi_n(\mathbf{X})$ is a target state of energy E_n in the absence of the laser field. $\omega_{n'n} = E_{n'} - E_n$ is the Bohr frequency, $e^{-i\mathbf{a}.\mathbf{R}}$ is a gauge factor, and $M^{\pm}_{n'n} = \varepsilon_0 \left\langle \psi_{n'} \left| \hat{\varepsilon}_\pm \cdot \mathbf{R} \right| \psi_n \right\rangle$ is the dipole coupling matrix elements.

To first order in the electron–atom interaction potential in the direct channel, the S-matrix element for the inelastic scattering, in the presence of the laser field is given by the expression [20]

$$\mathbf{S}^{B_1}_{f,i} = -i \int_{-\infty}^{+\infty} \mathrm{d}t \left\langle \chi_{k_f}(\mathbf{r}_0, t)\, \Phi_f(\mathbf{X}, t) \left| V_d(\mathbf{r}_0, \mathbf{X}) \right| \chi_{k_i}(\mathbf{r}_0, t)\, \Phi_i(\mathbf{X}, t) \right\rangle, \quad (6)$$

where

$$V_d(\mathbf{r}_0, \mathbf{X}) = -\frac{2}{r_0} + \sum_{j=1}^{2} \frac{1}{r_{0j}}, \quad (7)$$

the direct electron–atom interaction potential in the initial channel, $r_{0j} = |\mathbf{r}_0 - \mathbf{r}_j|$. $\mathbf{r}_0$ and $\mathbf{X}$ are, respectively, the projectile and target electron coordinates. By expanding the integrand in a Fourier series and integrating over t, we can recast Eq. (6) in the form

$$S^{B_1}_{f,i} = i(2\pi)^{-1} \sum_{l=-\infty}^{+\infty} \delta\left(E_{k_f} + E_f - E_{k_i} - E_i - \ell\omega\right) f^{B_1,\ell}_{f,i}(\boldsymbol{\Delta}). \quad (8)$$

The first-Born scattering amplitude, $f^{B_1,\ell}_{f,i}(\boldsymbol{\Delta})$, corresponding to the process $i \longrightarrow f$ accompanied by the transfer of ℓ photons, can be split in an electronic and an atomic amplitudes. They can be written as

$$f^{B_1,\ell}_{f,i}(\boldsymbol{\Delta}) = f^{B_1,\ell}_{elec}(\boldsymbol{\Delta}) + f^{B_1,\ell}_{atom}(\boldsymbol{\Delta}), \quad (9)$$

with

$$f^{B_1,\ell}_{\mathrm{elec}}(\boldsymbol{\Delta}) = -\frac{2}{\Delta^2} J_\ell(\lambda) \left\langle \psi_f \left| \tilde{V}_d(\boldsymbol{\Delta}, \mathbf{X}) \right| \psi_i \right\rangle, \quad (10)$$

$$f^{B_1,\ell}_{atom}(\boldsymbol{\Delta}) = f_1(\boldsymbol{\Delta}) + f_2(\boldsymbol{\Delta}), \quad (11)$$

$$f_1(\boldsymbol{\Delta}) = -\frac{i}{\Delta^2} \sum_n \left(\frac{J_{\ell+l}(\lambda)}{\omega_{ni} + \omega} - \frac{J_{\ell-l}(\lambda)}{\omega_{ni} - \omega} \right) M_{ni} \langle \psi_f | \tilde{V}_d(\boldsymbol{\Delta}, \mathbf{X}) | \psi_n \rangle, \quad (12)$$

and

$$f_2(\boldsymbol{\Delta}) = -\frac{i}{\Delta^2} \sum_n \left(\frac{J_{\ell-l}(\lambda)}{\omega_{fn} + \omega} - \frac{J_{\ell+l}(\lambda)}{\omega_{fn} - \omega} \right) M_{fn} \langle \psi_n | \tilde{V}_d(\boldsymbol{\Delta}, \mathbf{X}) | \psi_i \rangle, \quad (13)$$

where

$$\tilde{V}_d(\boldsymbol{\Delta}, \mathbf{X}) = \sum_{j=1}^{2} \exp(i\boldsymbol{\Delta}.\mathbf{r}_j) - 2. \quad (14)$$

J_ℓ is an ordinary Bessel function of order ℓ. The terms $f^{B_1,\ell}_{elec}(\boldsymbol{\Delta})$ and $f^{B_1,\ell}_{atom}(\boldsymbol{\Delta})$ are called, respectively 'electronic' (which corresponds to the interaction of the laser field with the projectile only) and 'atomic' (which includes the atomic dressing effects and thus describe the distortion of the target by the electromagnetic radiation). Here $\lambda = \boldsymbol{\Delta}.\boldsymbol{\alpha}_0$ and $\boldsymbol{\Delta} = \mathbf{k}_i - \mathbf{k}_f$ is the momentum transfer.