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Polarization effects in radiative recombination of an electron with a highly charged ion

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Abstract

The radiative recombination of an unpolarized electron with a polarized highly charged H-like ion in its ground state is studied. The absolute and relative values of the electron spin-flip contribution to the cross section of the process for various scattering angles and photon polarizations are calculated. It is shown that, in addition to the forward and backward directions, there are some other scattering angles of the emitted photon, where, at a fixed linear photon polarization, the spin-flip transition gives a dominant contribution to the differential cross section.

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1. Introduction

Recent developments in detector techniques [1] make feasible the observation of the polarization of hard X-rays at the GSI facilities. This has stimulated theoretical investigations of photon polarization effects in an energetic collision between highly charged ions and low-Z target atoms [2–4]. In [5], the radiative recombination of a polarized electron with a polarized H- and Li-like uranium in its ground state was investigated. A serious obstacle for experimental study of the latter process consists in preparing polarized electron and ion beams at the required concentration. A very promising method for preparing a polarized ion beam was recently proposed in [6]. The practical realization of this method would open new

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possibilities for studying ion–electron and ion–atom collisions.

In the present paper we consider the radiative recombination of an unpolarized electron with a polarized highly charged H-like ion in its ground state. The polarized ion absorbs the electron, while the emitted photon is registered by a polarization sensitive detector. This process may be denoted as "polarized photon radiative recombination" (PPRR).

To the zeroth order in $1/Z$ the PPRR process is equivalent to the recombination with a bare nucleus into the 1s state with one substate being blocked by the Pauli principle. Thus we neglect the interelectronic interactions compared to the electron–nucleus interaction.

The total cross section of the process is formed by so-called spin-flip and non-spin-flip contributions (see [5]). Normally, except for the forward and backward directions of the emitted photon, the spin-flip contribution, which is of pure relativistic origin, is much smaller than the non-spin-flip one. For this reason, up to now the spin-flip contribution was identified only in angular-differential measurements at the forward direction of the emitted photon [7]. However, varying the parameters of the photon polarization, one can find some other angles of the photon emission, where the spin-flip transition gives a dominant contribution to the differential cross section. We investigate this region for the case of $^{238}U^{91+}$ considering various initial electron energies. The absolute and relative values of the spin-flip contribution to the cross section of the process for various scattering angles and photon polarizations are calculated.

The paper is organized as follows. In the next section we give the basic formulas for calculation of the PPRR. Numerical results and their brief discussion are given in Section 3.

Relativistic units ($\hbar = m_e = c = 1$) are used throughout the paper.

2. Basic formulas

The differential cross section of the process under consideration is given by (see e.g. [8])

$$\frac{d\sigma}{d\Omega_f} = \frac{1}{2}\frac{(2\pi)^4}{\upsilon_i}\mathbf{k}_f^2 \sum_{\mu_i} |\langle b|e\alpha_\nu A_f^{\nu*}|p_i\mu_i\rangle|^2, \tag{1}$$

where $\mathbf{k}_f$ and υ_i are the photon momentum and the incident electron velocity, respectively, $\alpha_\nu = (1, \boldsymbol{\alpha})$ and $\boldsymbol{\alpha}$ is a vector incorporating the Dirac matrices,

$$|b\rangle = \begin{pmatrix} g_b(r)\Omega_{\kappa_b\mu_b}(\hat{\mathbf{r}}) \\ \mathrm{i}f_b(r)\Omega_{-\kappa_b\mu_b}(\hat{\mathbf{r}}) \end{pmatrix} \tag{2}$$

denotes the wave function of the polarized bound electron, $\kappa = (-1)^{j+l+1/2}(j + 1/2)$ is the quantum number determined by angular momentum and parity of the state, $\hat{\mathbf{r}} = \mathbf{r}/|\mathbf{r}|$,

$$A_f^\nu(\mathbf{x}) = \frac{\epsilon_f^\nu \exp(\mathrm{i}\mathbf{k}_f \cdot \mathbf{x})}{\sqrt{2k_f^0(2\pi)^3}} \tag{3}$$

is the wave function of the emitted photon, $k_f^0 = |\mathbf{k}_f| \equiv \omega$ is the photon energy, $\epsilon_f = (0, \mathbf{e}_f)$ is the photon polarization, $p_i = (\varepsilon_i, \mathbf{p}_i)$ and $|p_i\mu_i\rangle = \psi_{p_i,\mu_i(+)}(\mathbf{x})$ indicates the wave function of the incoming electron with a defined asymptotic momentum and a spin projection with respect to the direction of the electron momentum.

Defining a current vector by equation

$$\mathbf{j}(\mathbf{k}_f) = \langle b|\boldsymbol{\alpha}\exp(-\mathrm{i}\mathbf{k}_f \cdot \mathbf{r})|p_i\mu_i\rangle, \tag{4}$$

the differential cross section (1) can be represented as

$$\frac{d\sigma}{d\Omega_f} = \frac{2\pi^2\varepsilon_i\alpha\omega}{p_i}\sum_{\mu_i}|\mathbf{e}_f^* \cdot \mathbf{j}|^2, \tag{5}$$

where α denotes the fine-structure constant.

Assuming the linear polarization of the emitted photon, we describe it by real unit vector $\mathbf{e}_f$, which lies in the plane that is perpendicular to the photon momentum $\mathbf{k}_f$ and is characterized by an angle χ with respect to the reaction plane (see Fig. 1).

The cross section of the process, given by Eq. (5), includes the spin-flip and non-spin-flip contributions. We consider the incoming electron propagating in the positive z-direction and choose z as a quantization axis. Then the terms "spin-flip" and "non-spin-flip" strictly refer to $\mu_i = -\mu_b$ and $\mu_i = \mu_b$ with μ_i being the helicity of the incident electron. The relative value of the spin-flip contribution can be conventionally characterized by the ratio