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QED theory of multiphoton transitions in atoms and ions

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A B S T R A C T

This review surveys the quantum theory of electromagnetic radiation for atomic systems. In particular, a review of current theoretical studies of multiphoton processes in one and two-electron atoms and highly charged ions is provided. Grounded on the quantum electrodynamics description the multiphoton transitions in presence of cascades, spin–statistic behaviour of equivalent photons and influence of external electric fields on multiphoton in atoms and anti-atoms are discussed. Finally, the nonresonant corrections which define the validity of the concept of the excited state energy levels are introduced.

Contents

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1. Introduction

Multiphoton processes in atomic systems were first described in the frames of Quantum Mechanics (QM) in the very early years of the QM development. These first studies were restricted by the two-photon transitions between atomic states, discrete or continuous. The processes with really many photons became of crucial importance with invention of lasers when the induced radiation started to play the dominant role. A spontaneous multiphoton emission processes are ranged by Perturbation Theory (PT) parameter α^N, where N is the number of photons, $\alpha = e^2/\hbar c \approx 1/137$ (e is the electron charge, $\hbar$ is the Planck constant, c is the speed of light) is the fine structure constant, i.e. the probabilities of the process with large N values are quite small. For the induced radiation the PT parameter becomes $\sim N\alpha$. Therefore the description of laser radiation and the interaction of this radiation with the matter (atoms, molecules, solids) requires special methods which were developed in Laser Physics. The Laser Physics is out of the scope of this review, we will be interested only in spontaneous multiphoton processes. These processes also are of interest both for physics connected with laboratory experiments and for astrophysics. Theory of these processes appeared to contain some delicate problems which require application of Quantum Electrodynamics (QED) treatment; this concerns especially the cascade transitions.

The theory of the multiphoton transitions in atoms on the basis of QM started with the work by Göppert-Mayer [1], where two-photon transitions were described. The first evaluation of the strongly forbidden in the nonrelativistic limit two-photon decay $2s \to 1s + 2\gamma(\text{E1})$ in H atom was performed by Breit and Teller [2]. An accurate nonrelativistic evaluation of the two-photon $2s \to 1s + 2\gamma(\text{E1})$ decay rate in H-like ions was given in [3]. The first fully relativistic calculation of this transition was performed in [4]. Later this calculation was improved in [5,6]. QED corrections to the two-photon decay of $2s$ level in hydrogen and H-like ions were studied in [7]. Double- and triple-photon decays of metastable atomic states with forbidden single-photon decay were analysed in [8,9]. Two-photon decays $ns \to 1s + 2\gamma(\text{E1})$ with $n > 2$ and $nd \to 1s + 2\gamma(\text{E1})$ in H-like ions within the nonrelativistic approach were considered in [10,11].

Two-photon decay rates in two-electron atoms and ions with account of relativistic and QED effects were evaluated for $1s2s2^1S_0 \to (1s)^2 1^1S_0 + 2\gamma(\text{E1})$ transition in [12,13] for a wide range of nuclear charge Z values. Similar calculations of the decay rate $(1s2s)2^3S_1 \to (1s)^2 1^1S_0 + 2\gamma(\text{E1})$ were made in [14,13]. Two-photon decay $(1s2p)2^3P_0 \to (1s)^2 1^1S_0 + 2\gamma(\text{E1M1})$ in He-like ions with $50 \leqslant Z \leqslant 92$ was calculated in [15,16]. A general QED approach for the evaluation of the multiphoton transitions in atoms and ions was developed in [17,18]. This approach was based on the F. Low [19] theory of the spectral line profile in QED. In [17] the decay rate $(1s2p)2^3P_0 \to (1s)^2 1^1S_0 + 2\gamma(\text{E1M1})$ was evaluated for $30 \leqslant Z \leqslant 100$ in He-like