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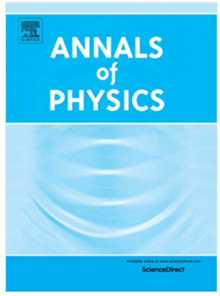

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Force on an electric/magnetic dipole and classical approach to spin-orbit coupling in hydrogen-like atoms

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Abstract

We carry out the classical analysis of spin-orbit coupling in hydrogen-like atoms, using the modern expressions for the force and energy of an electric/magnetic dipole in an electromagnetic field. We disclose a novel physical meaning of this effect and show that for a laboratory observer the energy of spin-orbit interaction is represented solely by the mechanical energy of the spinning electron (considered as a gyroscope) due to the Thomas precession of its spin. Concurrently we disclose some errors in the old and new publications on this subject.

1. Introduction

At the first time, the classical analysis of hydrogen-like atoms had been implemented by Thomas [1] in a view of the hypothesis about electron spin [2]. As is known, Thomas successfully explained the appearance of the multiplier ½ (the "Thomas half") in the expression for the spin-orbit interaction via the Thomas precession, which agreed with the measurement data. In 1926, Frenkel also derived the same expression for the spin-orbit coupling [3], considering the interaction of an electric dipole moment of orbiting electron, resulting due to relativistic transformation of its proper magnetic dipole moment to the labframe, with the electric field of nucleus. Later the correct expression for spin-orbit interaction has been obtained at a more fundamental level via the quantum relativistic electron theory of Dirac [4]. At the same time, the semi-classical explanation of this quantum effect remains comforting, sustaining the impression that we are capable to understand some results of quantum physics at the level of our intuitive perception. Besides, this way is definitely useful from the educational viewpoint. Due to these reasons, after the appearance of the classical works by Thomas [1] and Frenkel [3], numerous papers had been published on this subject till the present time. In the present contribution, we do not have the goal to provide a review of these papers; we only mention that they can be divided into two groups, where the analysis of spin-orbit coupling is carried out either in the rest frame of electron (like in the original publication [1]), or in the rest frame of nucleus (the laboratory frame, like in the publication [3]). We point out that the most recent publications on the subject [5-9] belong to the second group, i.e., they analyze the spin-orbit interaction for an observer in a laboratory frame. This analysis essentially involves the available expressions for the force on an electric/magnetic dipole in an electromagnetic field, as well as for the energy of dipole. However, as we have recently shown [10, 11] the known expressions for the force on a dipole were either incomplete or erroneous until the present time, and the correct solution of the problem of deriving a relativistically adequate equation for the force on an electric/magnetic dipole can be obtained via the Lagrangian approach. The obtained novel expression for the force on a dipole concurrently leads to the novel expression for the energy of a dipole in an electromagnetic field [10, 11].

Thus, the goal of the present paper is to reanalyze the classical approach to the spin-orbit coupling in hydrogenlike atoms, using the modern expressions for the force on a dipole and for its energy (sub-section 2.1). In this way, in sub-section 2.2 we derive a novel physical picture with respect to a laboratory observer, which concludes that at the level of fine interaction, the terms of electromagnetic origin in the interaction of the orbiting electron with the charged nucleus mutually cancel each other, so that the energy of spin-orbit interaction, from the classical viewpoint, is represented solely by the mechanical energy of the spinning electron (considered as a gyroscope) due to the Thomas precession of its spin. In the rest frame of electron, the spin-orbit