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Creation of vector bosons by an electric field in curved spacetime

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HIGHLIGHTS

- Duffin–Kemmer–Petiau equation is solved exactly in the presence of an electrical field.
- Solutions were made in $(1 + 1)$-dimensional curved spacetime.
- Particle creation rate for the de Sitter model is calculated.
- Pure gravitational or pure electrical field effect on the creation rate is analyzed.

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ABSTRACT

We investigate the creation rate of massive spin-1 bosons in the de Sitter universe by a time-dependent electric field via the Duffin–Kemmer–Petiau (DKP) equation. Complete solutions are given by the Whittaker functions and particle creation rate is computed by using the Bogoliubov transformation technique. We analyze the influence of the electric field on the particle creation rate for the strong and vanishing electric fields. We show that the electric field amplifies the creation rate of charged, massive spin-1 particles. This effect is analyzed by considering similar calculations performed for scalar and spin-1/2 particles.

1. Introduction

According to the Quantum Electrodynamics (QED), vacuum is unstable in the presence of strong electric fields and that leads to the creation of electron–positron pairs. The concept of pair production within the vacuum dates from the discovery of the Klein paradox [1], which was later treated by Sauter [2]. After these studies, different approaches were developed to analyze the particle production mechanism by external fields. Heisenberg and Euler discovered that particle–antiparticle pairs

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were created in vacuum by an electric field [3]. Subsequently, the instability of the vacuum, as suggested by QED, was completely formalized by Schwinger using the proper time method; it is called the Schwinger mechanism in QED [4]. Schwinger's nonperturbative formula is widely used for spatially homogeneous and static electric fields. Recently, electron–positron pair production has been investigated for alternating and pulse-shaped electric fields on the basis of the kinetic approach [5]. A detailed study on the particle creation by external electromagnetic fields in flat space can be found in Ref. [6].

In the field of modern theoretical physics, much attention is paid to the unification of the Quantum Field Theory (QFT) and general relativity. In the presence of the gravitational field, QFT is also associated with unstable vacua [7] and this instability leads to the emission of particle pairs due to the Hawking effect [8]. One useful way of building a unique theory of gravitation and QFT is to study the single particle equations. The quantum effects of the gravitational fields can be treated by the solutions of these equations.

The particle creation mechanism is one of the important problems in cosmology. It may enlighten the source of the great entropy in the present universe and its influence to convert the isotropic early universe to anisotropic [9]. The rate of the creation is calculated by studying relativistic particle equations in the presence of the external fields in curved spacetimes and this knowledge provides the thermal distribution of the studied particles and its relationship to thermodynamics.

External electromagnetic fields contribute significantly to the results of particle production phenomena treated in curved spacetimes. Many studies have been devoted to the particle creation phenomenon, using different universe models in the presence of electromagnetic fields [10–28].

In the present study, we analyze the particle production mechanism based on the DKP theory of massive spin-1 vector particles by considering the conjugate coupling of the gravitational and time-dependent electric fields. The goal is to calculate the effects of such fields on the creation of spin-1 particles, which are $W^{\pm}$ and Z bosons, in the $(1 + 1)$-dimensional de Sitter universe. Similar calculations have been performed by Refs. [25,26] for scalar (spin-0) and spinor (spin-1/2) particles in the same background and electric field. The noteworthy point of the results is that the electric field reduces the creation rate of spin-0 whereas it amplifies the purely gravitational spin-1/2 particle creation. Coupling of the spin–electric field should be one of the possible reasons of this difference. It is interesting to evaluate whether contribution coming from spin–electric field coupling should also be verified by the higher spin-valued particles, namely spin-1 particles. This is one of the goals of our calculation and will be discussed in the conclusions.

General relativistic forms of the particle equations in four dimensions are difficult to solve exactly. Different approaches were proposed to solve them, such as weak field approximation, numerical methods, asymptotic solutions and WKB approximations. This adversity can be by-passed by reducing the number of spatial dimensions. Then dynamics of particle is restricted to a lower-dimensional spacetime and some elements like spin coupling to the external field are not seen explicitly in the exact solutions, but that is already not required for the calculation of the particle creation rate. The resulting equation for the particle takes a simpler form and still maintains the physical insight to the problem. Physically considerable lowest spacetime-dimension is $(1+1)$, we will consider the de Sitter line element for our calculations:

$$ds^2 = -dt^2 + e^{2Ht}dx^2. \tag{1}$$

It reduces to a conformally flat spacetime form

$$ds^2 = \frac{1}{H^2\eta^2}(-d\eta^2 + dx^2) \tag{2}$$

with the conformal time definition given by $\eta = -\frac{1}{H}e^{-Ht}$. Gravitational fields propagate conformally in this spacetime.

The layout of the study will be as follows. The general formalism of the calculation for the particle creation mechanism will be introduced in Section 2. In Section 3 exact solutions of the DKP equation will be obtained for the cosmological model in which we are interested with a time-dependent electric field and "in" and "out" vacuum states will be identified. Then we calculate the rate of particle creation. Finally in Section 4 we analyze the relation which was obtained for particle creation rate for different values of the electric field.