Pair creation in electric fields, anomalies, renormalization, and backreaction

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We consider pair production phenomena in spatially homogeneous strong electric fields. We first study scalar QED in four-dimensions and discuss the potential ambiguity in the adiabatic order assignment for the electromagnetic potential required to fix the renormalization subtractions. This ambiguity can be fixed by invoking the conformal anomaly when both electric and gravitational backgrounds are present. We also extend the adiabatic regularization method for spinor QED in two-dimensions and find consistency with the chiral anomaly. We have studied numerically the semiclassical Maxwell equations with the adiabatic subtraction terms of the proper adiabatic order.

Keywords: Schwinger effect; pair creation; adiabatic renormalization; semiclassical Maxwell equations.

1. Introduction

A time-dependent gravitational field yields the creation operators of quantum fields to evolve into a superposition of creation and annihilation operators. This produces the spontaneous creation of particle-antiparticle pairs. This effect was first discovered and widely analyzed in the physical context of an expanding universe. In the early seventies, a similar transformation between creation and annihilation operators was proved to occur for accelerated observers in the Rindler wedge of Minkowski space and also in the spacetime describing a gravitational collapse forming a black hole. Subsequent investigations concluded that gravitons are also created by the expansion of the universe. Shortly after the proposal of the inflationary universe, the creation of scalar perturbations was widely analyzed. A similar superposition of creation and annihilation operators takes place if the quantized field is coupled to a time-varying scalar field background. Therefore, particle creation can be enhanced after the end of inflation, when the inflation, regarded as an external scalar field coupled to quantized matter fields, starts to rapidly oscillate in time.

In this contribution we want to focus on the particle creation phenomena caused by a time varying background gauge field. These electromagnetic processes are strongly motivated by the upcoming high intensity and ultrashort laser experiments, which will allow us to understand non-perturbative regimes in QED where vacuum particle creation becomes relevant. The most paradigmatic example of this is the pair-production by a strong and spatially homogeneous electric field $\vec{E}(t) = E(t)\hat{x}$, where one assumes a configuration with an initial vanishing electric field $E(t) \to 0$ as $t \to -\infty$, an intermediate period with a smoothy varying electric field, and a final decay to a zero electric field $E(t) \to 0$ when $t \to +\infty$. A prototype for this is the pulsed configuration $\vec{E} = (E_0 \cosh^{-2}(\omega_0 t), 0, 0)$. In the limit $\omega_0 \to 0$ one recovers the constant electric field, which is actually an inherent assumption in the well-known Schwinger effect. Schwinger's derivation, extending previous work by Sauter and Heisenberg and Euler, is obtained within the effective action formalism in quantum electrodynamics (QED). It has been of great interest in theoretical research over many years and it may be at the border of being experimentally verified.

A fundamental problem in gravitational processes is the calculation of the expectation values $\langle T_{\mu\nu} \rangle$, which, in addition to provide definite quantities for energy density, pressure, or radiation fluxes, would act as the proper source for the (semi-classical) Einstein's equations. The computations are involved, as we have to deal with ultraviolet (UV) divergences not present in Minkowski space. The corresponding subtractions needed for renormalization requires more sophisticated methods. Equivalently, in a time-dependent electric field the proper source of the Maxwell equations is the electric current which again posseses UV divergences. In this work we analyze the renormalization of the electric current $\langle j_\mu \rangle$ for spatially homogeneous electric fields by importing and extending renormalization methods originally proposed in cosmological scenarios. The electric current is probably the most important local observable to be consider in a near-future detection of the Schwinger effect. Therefore, the renormalization of both observables $\langle T_{\mu\nu} \rangle$ and $\langle j_\mu \rangle$ merit a detailed and simultaneous analysis. Moreover, new interests in cosmological scenarios of the Schwinger effect demand the need of a regularization method involving both electric and gravitational fields.

The goal of this contribution is to further extend the adiabatic regularization method for scalar and Dirac fields living in a Friedmann-Lemaitre-Robertson-Walker (FLRW) spacetime by adding the interaction with an external homogeneous electric field.

2. Main achievements

In this work we have improved the adiabatic regularization method to include homogeneous electric fields. Our extension of the method has two folds. On the one hand, we have reexamined the method to dead with both electric and gravitational fields on an equal footing and for a quantized scalar field. In doing this we have fixed an inherent ambiguity of the method. The adiabatic order assignment of the vector potential has been traditionally assumed in the literature of zero order. Here we have argued that the correct adiabatic order assignment is one, instead of zero, at least if a gravitational field is present. This problem has been fixed by invoking the conformal anomaly. On the other hand, we have extended the adiabatic method to dead with fermions in two-dimensions. We have checked the consistency of our method by reproducing the axial anomaly. One of the main advantages of the adiabatic method in the capability to perform numerical computations. We have studied numerically the semiclassical Maxwell equations with the adiabatic subtraction terms of the proper adiabatic order. We have also checked numerically the semiclassical conservation of the energy. The physical predictions are sensitive to the theoretical improvements of the renormalization method.

References

1. J. Schwinger, *Phys. Rev.* **82**, 664 (1951).
2. L. Parker and D. J. Toms, *Quantum Field Theory in Curved Spacetime: Quantized Fields and Gravity*, Cambridge University Press, Cambridge, England (2009).
3. L. Parker and S. A. Fulling, *Phys. Rev. D* **9**, 341 (1974)
4. I. Agullo, J. Navarro-Salas, G. J. Olmo and L. Parker, *Phys. Rev. Lett.* **103**, 061301 (2009);
5. A. Landete, J. Navarro-Salas and F. Torrenti, *Phys Rev. D* **88**, 061501 (2013); *Phys. Rev. D* **89**, 044030 (2014). A. del Rio, A. Ferreiro, J. Navarro-Salas and F. Torrenti, *Phys. Rev. D* **95**, 105003 (2017).
6. A. Ferreiro and J. Navarro-Salas, *Pair creation in electric fields, anomalies, and renormalization of the electric current*, arXiv:1803.03247.
7. T. Kobayashi and N. Afshordi, *J. High Energy Phys.* **10**, 166 (2014).
8. C. Stahl, E. Strobel and S.-S. Xue, *Phys. Rev. D* **93**, 025004 (2016).
9. Y. Kluger, J. M. Eisenberg, B. Svetitsky, F. Cooper and E. Mottola, *Phys. Rev. Lett.* **67**, 2427 (1991).
10. I. Agullo, A. del Rio and J. Navarro-Salas, *Int. J. Mod. Phys. D* **26**, 1742001 (2017); *Phys. Rev. Lett.* **118**, 111301 (2017).
11. G. V. Dunne, G. V. Dunne, *Int. J. Mod. Phys. A* **27**, 1260004 (2012); *Eur. Phys. J. D* **55**, 327 (2009).