Adiabatic invariance in the creation of particles by gravitational and electromagnetic fields

Pau Beltrán-Palau,[1,*] Antonio Ferreiro,[1] Jose Navarro-Salas,[1] and Silvia Pla[1]

[1] *Departamento de Fisica Teorica and IFIC, Centro Mixto Universidad de Valencia-CSIC. Facultad de Fisica, Universidad de Valencia, Burjassot-46100, Valencia, Spain.*

Particles are spontaneously created from the vacuum by time-varying gravitational or electromagnetic backgrounds. It has been proven that the particle number operator in an isotropically expanding universe is an adiabatic invariant, irrespective of the value of the mass. In this work we show that, in some special cases and always for massless Dirac fields, the expected adiabatic invariance of the particle number breaks down in presence of electromagnetic backgrounds. We also show a close relation between this breaking of the adiabatic invariance and the emergence of the axial anomaly. We illustrate this fact with several examples, either using Bogoliubov transformations or evaluating the renormalized electric current.

The proper understanding of the particle creation phenomena, via Bogolubov transformations, was pioneered in the analysis of quantized fields in an isotropically expanding universe [1–3]. A fundamental issue in the study of particle creation in an expanding universe was the adiabatic invariance of the number of created particles. The particle number of a quantized field, in the limit of an infinitely slow and smooth expansion of the universe, does not change with time [4], even if the quantized field is massless. In other words, the density of created particles by the expanding universe approach zero when the Hubble rate $\dot{a}/a$ is each time negligible even if the final amount of expansion $a(t_{final})/a(t_{initial})$ is large. Moreover, pair production can also take place in time-varying electric backgrounds [5], and it can be regarded as a very important non-perturbative process in quantum field theory [6].

The main purpose of this work is to generalize the analysis of the adiabatic invariance of the particle number observable in presence of an electromagnetic background. We find that, for massive fields, adiabatic invariance is, as expected, preserved. For slowly varying electromagnetic potentials no quanta is being produced, even if the change in A_μ over a long period is very large. However, in some cases and only for massless Dirac fields, the particle number is not an adiabatic invariant. We analyze the problem in detail in a two-dimensional scenario, for both scalar and Dirac fields. The main results can be easily translated to four dimensions. As a by-product of our analysis, we point out a connection between the (anomalous) breaking of the adiabatic invariance of the particle number operator and the emergence of a quantum anomaly in the chiral symmetry. The requirements for the non-conservation of chirality seems to be directly related to those found for the breaking of the adiabaticity in the particle number observable. Concerning the renormalization, it is convenient in this context to use the adiabatic renormalization method [1–3] for a scalar field in a gravitational background, and recently extended for a Dirac field [7, 8] and for an electric background [9, 10].

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* Proposed speaker (pau.beltran@uv.es)