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Perturbative neutrino pair creation by an external source

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Abstract

We consider the rate of fermion–antifermion pair creation by an external field. We derive a rate formula that is valid for a coupling with arbitrary vector and axial vector components to first order in perturbation theory. This is then applied to study the creation of neutrinos by nuclear matter, a problem with astrophysical relevance. We present an estimate for the creation rate per unit volume, compare this to previous results and comment on the role of the neutrino mass.

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1. Introduction

Starting with Schwinger's classical account [1] of electron–positron pair creation by an external electric field, fermion pair creation has been the subject of continued interest. A variety of pair creation rates for specific external fields in quantum electrodynamics can be found in the literature, such as Refs. [2–10] and further references therein. The process exemplifies a true quantum field theory phenomenon: the creation of particles from the vacuum.

Because neutrinos carry weak charge, one expects that an external Z-boson field can produce neutrino–antineutrino pairs in a similar manner. The concept of an external Z-boson field can be seen as arising from a distribution of nuclear matter (in the sense of Ref. [11]). Neutron stars are a prime example of such a matter distribution and their neutrino emission by this mechanism was studied using non-perturbative methods [11–13]. Pair creation of neutrinos is also studied in relation to the stability of neutron stars, see Ref. [14] and references therein. Although Refs. [11–13] find typical neutrino fluxes that are too small to be observable, we believe it is worthwhile

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to study such a relatively unexplored neutrino source from a different point of view. In particular, we want to develop a method that is not limited to a specific source but allows us to draw conclusions with a broad applicability. This can then be applied to study, e.g., neutrino pair creation by non-standard model weakly interacting particles or domain walls.

In the present Letter, we study the creation of neutrino pairs in a perturbative way. We present a first order computation of the pair creation rate per volume, with a dynamical nuclear configuration acting as a source. The reasons for using perturbation theory are twofold. First, the axial coupling to the Z-boson prevents an easy generalization of non-perturbative QED methods. Second, non-perturbative methods generally consider a very specific source, or class of sources, from the start. The perturbative method is more flexible in the sense that a specific source is folded in at the end. This allows us to keep separate the physics of the pair creation process and that of a specific source.

In part, our computation was triggered by the results presented in Ref. [11], in which the creation of neutrinos by a time-dependent nuclear distribution is studied. One of the results in Ref. [11] is that the overall rate is proportional to the square of the neutrino mass. This implies that there can be no pair creation of massless neutrinos. The question arises whether this is a manifestation of a general chiral suppression mechanism or a consequence of the specific source considered. We shall see that the perturbative viewpoint contributes to a more complete understanding of this effect.

The Letter is organized as follows. In Section 2 we discuss the theoretical background of pair creation processes for fermions and introduce the relevant quantities. In Section 3, we discuss the perturbative computation. The result is then applied to neutrinos in Section 4 and we present our conclusions in Section 5.

2. Pair creation physics

We study fermions that are coupled to an external source j. The interaction Lagrangian reads

$$\mathcal{L}_{\text{int}} = j_\mu(x)\bar{\psi}(x)\Gamma^\mu\psi(x). \tag{1}$$

The source is fully prescribed and has no further dynamics. We choose the coupling of the general form

$$\Gamma^\mu = \gamma^\mu\left(c_V - c_A\gamma^5\right), \tag{2}$$

where c_V (c_A) is the vector (axial vector) coefficient; the coupling constant is absorbed in j.

Following Ref. [15], we introduce the overlap of asymptotic 'in' and 'out' vacua to describe the pair creation process:

$$S_0(j) = \langle 0, \infty|0, -\infty\rangle_j = \langle 0, \infty|S|0, \infty\rangle_j, \tag{3}$$

where S is the scattering operator and the subscript is a reminder that a source is switched on and off adiabatically somewhere between $t = -\infty$ and $t = \infty$. The probability that a system that started in the vacuum state will remain in the vacuum state is then expressed [15] as

$$\left|\langle 0, \infty|0, -\infty\rangle_j\right|^2 = \exp(-W) = \exp\left(-\int d^4x\, w(x)\right). \tag{4}$$

For a positive W, this probability is between zero and one which signals a non-zero probability for the creation of a fermion pair. Now suppose that $w(x) = \bar{w}$ is constant. We can embed the system in a box of size $V \times T$, write $W = \bar{w}VT$ and choose the box small enough such that $W < 1$:

$$\left|\langle 0, \infty|0, -\infty\rangle_j\right|^2 \simeq 1 - \bar{w}VT, \tag{5}$$

which supports the interpretation of the function $w(x)$ as the probability per unit time and volume to create a pair at space–time location x. Such a rate density is the physical quantity of interest. For QED, the Schwinger formula