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Note on invariant properties of a quantum system placed into thermodynamic environment

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HIGHLIGHTS

- Invariant properties of a quantum system are affected by thermodynamic environment.
- CP-violating systems may seem CPT violating due to thermodynamic interference.
- These conclusions are consistent with CPT discrepancies observed in CP-violating kaon decays.

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ABSTRACT

The analysis conducted in this work indicates that interactions of a CP-violating (and CPT-preserving) quantum system with a thermodynamic environment can produce the impression of a CPT violation in the system. This conclusion is reasonably consistent with the results reported for decays of neutral K-mesons.

1. Introduction

The influence of a thermodynamic environment, commonly referred to as a thermodynamic bath, on quantum systems has been repeatedly discussed in publications. Zurek [1] introduced a theory explaining loss of coherence in a quantum system under the influence of the environments that have a large number of degrees of freedom. Goldstein et al. [2], Popescu et al. [3] and others demonstrated the property called canonical typicality: for most pure states of the environment, the quantum system behaves as if the environment was in the thermodynamic (i.e. maximally mixed) state. Linden et al. [4] proved that under certain conditions the evolution of a quantum system placed into a bath leads to equilibration. These and other aspects of thermalisation have been reviewed by Yukalov [5], who stressed that, practically, any quantum system cannot be completely isolated and is subject to some influence from the environment. The existence of a degree of similarity between thermodynamic and pure-state quantum engines has been discussed by Abe [6].

The goal of the present work is to show that thermodynamic environment can affect the apparent invariant properties of a quantum system, whose intrinsic behaviour involves a CP-violation. Here we refer to charge, parity and time symmetries conventionally denoted by C, P and T in quantum mechanics [7]. While the overwhelming majority of known quantum effects are CP-compliant, the case of CP violation in decay of K-mesons (kaons) has been known and investigated for many decades [8].

While the present work focuses on the effects induced by the environment (assuming conventional unitarity of quantum evolutions) the likelihood of spontaneous (intrinsic) violations of quantum mechanics, which can coexist with induced mechanisms and also be responsible for thermalisation, has been repeatedly discussed in publications [9–11]. The possibility

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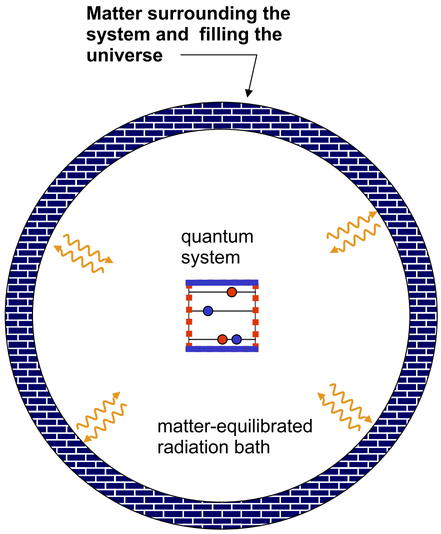

Fig. 1. Quantum system placed into a radiation bath.

that these violations can affect decays of K-mesons has been raised by Ellis et al. [12]. Although the influence of spontaneous violations of quantum mechanics cannot be excluded a priori and needs to be considered, such violations remain outside the scope of the present work. Here, we consider the influence of the environment within the framework of conventional quantum mechanics while relying on causality and the proper choice of parameters to reproduce the thermodynamic direction of time.

2. Quantum system in a radiation bath

Consider a quantum system, which involves both particles and antiparticles and is placed into the environment filled by radiation. The radiation is equilibrated by surroundings, which, of course, are made of matter prevalently present in the universe. The system under consideration is a quantum system but is subject at least to some thermodynamic influence from the environment. Since antiparticles cannot interact weakly (i.e. without annihilations) with an environment formed by matter, these interactions are performed only through radiation, which is always generated by the surrounding matter having non-zero temperatures. Note that we do not consider a stronger interaction of the quantum system with radiation through emission or adsorption. Only very weak interactions of the system and radiation that tend to impose quantum decoherence on the system [1,5] are of interest, while radiation refers to any field that can be responsible for such interactions. The system placed in a radiation bath, which is equilibrated by surroundings, is schematically depicted in Fig. 1. This scheme of interactions of the system and the environment through the radiation bath reflects the fact that surrounding matter needs to be removed from direct contact with the system that involves both particles and antiparticles. We conduct our analysis within the limits of quantum mechanics and take into account the thermodynamic direction of time through causality and choice of the interaction parameters.

The state of the radiation bath is characterised by its set of energy eigenstates $\mathbb{H}_B \left|\beta\right\rangle = E_\beta \left|\beta\right\rangle$. The dimension of this system is very large. In the same way, the state of the environment, which, as some publications [3] prefer to describe, may involve the rest of the universe, is characterised by an even larger set of eigenstates $\mathbb{H}_\Omega \left|\Omega\right\rangle = E_\Omega \left|\Omega\right\rangle$. The state of the system can be described by a set of orthogonal ket states $|s\rangle$. Hence the overall state of the universal system involving the system, the bath and the environment is specified by vectors in the tensor product space $|s\rangle \otimes |\beta\rangle \otimes |\Omega\rangle$ (with the corresponding bra space $\langle s| \otimes \langle\beta| \otimes \langle\Omega|$). Our analysis is conducted under several assumptions, which can be summarised by:

1. the quantum system is small and connected to a much larger environment through the radiation bath;
2. the radiation bath can exercise some influence on the system;
3. the system has little effect on the bath, which is equilibrated by the environment and remains in a thermodynamic state.

Our use of the words "strong" and "weak" generally pertains to a common understanding of these terms, which nevertheless does not exclude links with the strong and electroweak interactions of particle physics. Although the presence of the environment must always be kept in mind, our assumptions lead to autonomous consideration of the supersystem, which involves only the system and the radiation bath. The state of the supersystem is specified by the tensor product, which can be equivalently denoted by $|s\rangle \otimes |\beta\rangle = |s\rangle\,|\beta\rangle = |s\beta\rangle$. Note that we do not intend to demonstrate that the bath should be in its thermodynamic state but simply introduce this physical fact as a principal postulate of our analysis.