CONNECTIONS BETWEEN THERMODYNAMICS, STATISTICAL MECHANICS, QUANTUM MECHANICS, AND SPECIAL ASTROPHYSICAL PROCESSES

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Abstract

This article discusses several diverse “zero-point” notions, ranging from early classical blackbody radiation analysis, to astrophysical and cosmological considerations now being contemplated. The now commonly accepted quantum mechanical meaning of “zero-point” is compared with the early historical thermodynamic meaning. Subtle points are then reviewed that were implicitly imposed in the early thermodynamic investigations of blackbody radiation. These assumptions prevented this analysis from applying to the situation when classical electromagnetic radiation does not vanish at temperature $T=0$. These subtle points are easy to skip over, yet significantly change the full thermodynamic analysis. Connections are then made to some proposed mechanisms involved in various astrophysical processes. The possible connection with the observed increasing expansion of the universe is noted, and the increasing inclination of scientists to attribute this expansion to “vacuum energy.” However, since the universe is not in a state of thermodynamic equilibrium, then the commonly accepted notion of “vacuum energy” or “zero-point” energy may not really be accurate. Altering this perspective may be helpful in coming to terms with the full physical description.

1. Introduction

The present article touches on a combination of several overlapping topics, with an attempt made to connect all these topics together at the end. To begin, a brief historical perspective is presented in Sec. II on the early meaning of “zero-point” (ZP), as in regards to the state of atomic systems near absolute zero temperature, and contrasted to the almost universal reference now used as the lowest quantized energy state of a system. A quantum mechanical perspective certainly provides a relation between these two concepts, but, as discussed here, the modern point of view is significantly different than the one first envisioned.

Such thoughts naturally lead one to examine the meaning of thermodynamic equilibrium, both from the more macroscopic perspective of conventional

thermodynamics, but then as regards smaller and even “single" atomic systems in interaction with the infinite number of radiation modes. Such a discussion is indeed a fascinating one and requires a deep examination. Planck tackled aspects of these problems in his treatise in Ref. [1]. He introduced several devices for aiding the discussion of the thermodynamic behavior of radiation, such as a black carbon particle" and rough scattering walls. His treatment of rays of heat radiation in a cavity included the concept that each ray could be described by a separate temperature, where the state of maximum entropy occurred when all rays were at the same temperature. Many of these concepts are still useful constructs today, and indeed can provide means for experimental testing in quantum cavity electrodynamics.

However, as discussed in Sec. III, some of these early ideas by Wien, Planck, and others, led to unnecessary restrictions on the thermodynamic analysis of electromagnetic radiation. Indeed, much of the early ideas implicitly restricted the Wien displacement analysis from applying to radiation that at absolute zero temperature did not reduce to zero radiation. These restrictions prevented the early analysis from being sufficiently general to take into account Casimir-like force considerations. These subtle points are easy to skip over, yet significantly change the thermodynamic analysis of a system.

This article ends by making some connections to mechanisms in proposed astrophysical processes involving the secular acceleration of particles, such as may be a contributor for cosmic ray formation. The possible connection with the observed increasing expansion of the universe is noted, and the increasing inclination of scientists to attribute this expansion to “vacuum energy.” This brings the present discussion back full circle, by bringing in the notion that the universe is not in a state of thermodynamic equilibrium, so the commonly accepted notion of “vacuum energy,” or “zero-point" energy, may not really be accurate. Altering this perspective should be helpful in coming to terms with the full physical description.

2. Zero Point

It is interesting to note the original historical meaning of “zero-point" as having to do with the observed nonvanishing kinetic energy of systems near the point of absolute zero temperature [2]. In contrast, the modern perspective and emphasis on the term “zero-point" is really quite different. Indeed, very often in the textbooks on quantum physics, as well as in the physics literature, the terminology of the “ZP state" and the “ZP energy" of a system is used interchangeably with the “ground state" and the “ground-state energy," without ever mentioning temperature or thermal equilibrium conditions [5]. Indeed, in keeping with this modern perspective, it’s likely that most students in physics today directly associate ZP with the lowest (“zeroth") energy quantum state, rather than with the state of a system at zero temperature.

Now, of course, in the quantum mechanics (QM) perspective, the ground state is equivalent to the state of the system at $T= 0$, so technically, this viewpoint is certainly correct. In QM, the ground state of a physical system is the state with the lowest possible quantized energy level. We assume that the ground state of a system is nondegenerate, which is the usual assumption made.