LETTERS TO PROGRESS IN PHYSICS

Experimental Proposal to Test Photon-Photon Scattering in a Blackbody Radiation Cavity

Guofeng Chang
Beijing University of Posts and Telecommunications, China
E-mail: 648892685@qq.com

We build a nonreciprocal blackbody concept based on the 2014 work of Linxiao Zhu and Shanhui Fan, who discovered nearly full breakdown of detailed balance in thermal radiation. If a closed isolated cavity uses this material as its inner surface, thermal equilibrium can never be achieved inside the cavity. To resolve this contradiction, we propose the photon-photon scattering hypothesis and design a corresponding experimental test in this paper.

Introduction

Kirchhoff proposed the ideal blackbody concept to simplify derivations [1], his innovative cavity design bears deep implications for fundamental physics, and his reasoning merits careful inspection. In our view, instead of a strict mathematical proof for thermal emission and absorption laws, Kirchhoff relied mainly on insightful physical intuition to define the ideal blackbody and make these laws nearly self-evident. This aspect attracted widespread criticism of his theory [2–4]. Nevertheless, several studies revisit these critiques and confirm Kirchhoff's law remains intact via consistent predictive results [5, 7].

A notable theoretical framework was developed by Linxiao Zhu and Shanhui Fan [4]. Their work proves that under certain physical constraints, the directional spectral emissivity and absorptivity of a material can strictly diverge along a fixed propagation direction:

$$e(\omega, \theta, \varphi) \neq \alpha(\omega, \theta, \varphi),$$

where e denotes the directional spectral emissivity, α denotes the directional spectral absorptivity, ω represents angular frequency, and θ and φ jointly characterize the radiation direction. This intrinsic material property is physically objective and conforms to theoretical deduction, which almost inevitably leads to the inference that detailed balance is violated — an essential premise underpinning Kirchhoff's original proof [1].

Building upon this theoretical viewpoint and Kirchhoff's classic ideal blackbody model, we propose the concept of the nonreciprocal blackbody. For such an idealized material, one propagation direction satisfies $e = 1$, $\alpha = 0$, $r = 1$, whereas another direction satisfies $e = 0$, $\alpha = 1$, $r = 0$. We term these two directions the full-emission-direction (short for FED) and full-absorption-direction (short for FAD), respectively; all other directions behave identically to a standard ideal blackbody, here r stands for the directional spectral reflectivity and both directions are arbitrarily defined. Although this abstraction originates from the findings of Linxiao Zhu and Shanhui Fan, it may seem highly arbitrary at first sight, leading readers to regard it as valueless and theoretically insignificant. Upon closer inspection, however, this new concept bears no fundamental difference from Kirchhoff's ideal blackbody. It only incorporates one extra physically justified assumption on top of Kirchhoff's original idealizations, and this supplementary postulate may hold even stronger physical plausibility compared with the standard ideal blackbody hypothesis. Both models abide by fundamental physical laws without internal theoretical conflicts. If physical conclusions derived from the traditional ideal blackbody model are considered reliable, results obtained via our nonreciprocal blackbody model should likewise be regarded as trustworthy.

Consider an adiabatically isolated and fully enclosed cavity coated with nonreciprocal blackbody material, apart from two small ideal blackbody surfaces A and B. Owing to the arbitrariness of FED and FAD orientations, all FEDs can point toward A while all FADs point toward B. For any surface other than A and B, surface A absorbs both incident radiation and reflected self-radiation from these surfaces, leading to a rising temperature. By contrast, surface B continuously radiates internal energy and gradually cools down. Even with effective thermal conduction between A and B, the temperature of A inevitably exceeds that of B. This directly contradicts the fundamental feature of cavity thermal equilibrium, in which all surface elements possess identical temperatures.

If we insist on retaining both the idealized concept of the nonreciprocal blackbody and the well-established thermodynamic empirical law that isolated equilibrium systems feature uniform temperature distribution, intracavity photons become the only suspect responsible for the above contradiction. This is exactly the hypothesis proposed in this paper: in a thermally equilibrated cavity, photons serve as a direction eraser through photon-photon scattering, converting anisotropic, inhomogeneous radiation into isotropic and uniform cavity radiation and making the intracavity vacuum behave as if it undergoes spontaneous radiation. Combined with Kirchhoff's

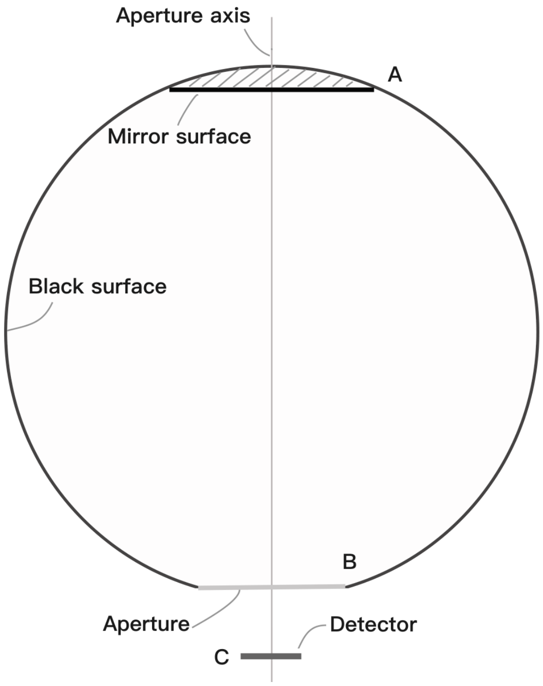

Fig. 1: Schematic diagram of the experimental proposal.

description that "...for infinitely small thickness, completely absorb all rays which fall upon them. I will call such bodies perfectly black, or more briefly black" [1], we argue that the cavity wall together with its adjacent photons under thermal equilibrium jointly constitutes an ideal blackbody with material-independent universality. We further present experimental descriptions to characterize the photon-photon scattering phenomenon, which appears as intrinsic vacuum radiation; we validate the former indirectly through the observation of the latter. Although the exact physical magnitude cannot be inferred from the proposed experiment, the present hypothesis is physically well-founded and highly consistent with Kirchhoff's theoretical inferences, making the current proposal particularly encouraging.

The experimental proposal

In Kirchhoff's radiation theory, blackbody cavity radiation is material-independent, with cavity walls acting as the primary radiation source. In practical experiments, however, blackbody-like high-emissivity coatings are widely employed to accelerate thermal equilibrium and optimize radiative balance [8]. When a small mirror is placed inside the blackbody cavity facing the aperture, the system still yields standard blackbody radiation after reaching thermal equilibrium. Given the rectilinear propagation of light, we can collect radiation within a sufficiently narrow viewing angle. The radiation in this angle solely originates from mirror reflection and intrinsic thermal emission of the mirror itself. If the measured radiation still converges to ideal blackbody distribution, it can be concluded that photon-photon scattering occurs inside the cavity.

As illustrated in the schematic diagram, the spherical cavity, internal mirror, aperture, and detector are all approximated as circular planar components. Here, point A marks the intersection of the mirror and the cavity wall, point B marks the edge of the aperture, and point C represents the endpoint of the detector. Except for the embedded mirror, the entire inner cavity is coated with conventional near-blackbody radiative material [8]. The radiative light path originating from the cavity wall at point B reflects from the mirror surface and finally reaches point C. The angle is defined as θ_1, while θ_2 denotes the viewing angle for direct radiation from the cavity wall at point A to the detector at point C. Both θ_1 and θ_2 represent the minimum viewing angles that eliminate stray radiation from other black cavity surfaces. Taking the smaller of these two angles ensures that the radiation collected within this angular range originates purely from the mirror, with no contamination from other cavity blackbody sources.

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