Does the blackbody radiation spectrum suggest an intrinsic structure of photons?

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Photons are considered to be elementary bosons in the Standard Model. An assumption that photons are not elementary particles is assessed from an outlook of equilibrium statistical mechanics with insights from computer simulation.

I. INTRODUCTION

In the derivation of his formula, Planck utilized the product of two factors: the spatial density of radiation energy (in parentheses) and the mean energy U_ν for resonators of frequency ν [1]:

$$u_\nu d\nu = \left(\frac{8\pi\nu^2}{c^3}\right)U_\nu d\nu . \tag{1}$$

The resonators can accommodate an integer number of energy quanta $h\nu$, so the mean energy at temperature T is

$$U_\nu = \frac{h\nu}{e^{h\nu/k_B T}-1} . \tag{2}$$

The constants above: Boltzmann's k_B, Planck's h, and the speed of light c.

While, after the introduction of quanta by Planck, the quantization ideas had flourished in a variety of physical applications, the radiation density (above) had not been understood in the same classical, statistical terms as energy quanta. Only after 24 years, Bose came up with a new counting of states. That was the invention of quantum statistics with "different species of quanta each characterized by the number N_s and energy $h\nu_s$ ($s=0$ to $s=\infty$)" [2].

With the quick development of quantum theories in the mid-1920s, the physics community became more acceptive of new probabilistic/statistical ideas. Even if Bose's derivation of Planck's formula was "obscure" (in Einstein's words) and Bose himself did not fully recognize his departure from classical statistics[1], the new suggestions could be postulated and used. The new probabilities were not necessarily rooted in underlying microscopic dynamics

[1] "I was not a statistician to the extent of really knowing that I was doing something which was really different from what Boltzmann would have done, from Boltzmann statistics." (as quoted in [3])

but rather heuristically determined. For example, in quantum electrodynamics: "… the price of this great advancement of science is a retreat by physics to the position of being able to calculate only the *probability* that a photon will hit a detector, without offering a good model of how it actually happens … theoretical physics has given up on that" [4]. To be fair, many modern tools of equilibrium statistical mechanics would not be viable without computers a century ago.

Time reversal invariance is an important notion in classical and quantum physics. Nowadays, one can build a working model of a statistical system from the bottom up – from assumptions of time-reversible microdynamics and keep track of every element and actually reverse the evolution of entire system. It can be done with a cellular automata simulation that reproduces classical statistics with Plank's mean energy factor (2) for a single mode of radiation [5]. However, the expansion of this method into multiple species of quanta in Bose reasoning looks problematic: the reversibility implies conservation of information and input states (cells) should always be uniformly mapped to the same number of output states, or the mapping function cannot be reversible. The symmetrical (bijective) mapping cannot be done between different numbers of states for two or more species. Thus, the Bose logic for multiple species of quanta is not reversible. Different energy for particles of different species does not help in energy exchange between species either. This disconnection or "retreat" from principles of underlying microdynamics remains often overlooked.

There are other ways to expand the cellular system while staying on a causal, reversible basis. It can be done by adding integer characteristics to the states (cells). The grid can be more than 2-dimensional. One can treat the cell attributes as representation of internal components of a composite structure and study statistical distributions for a variety of possible formations. Moving forward these approaches would be challenging and progress would be quite limited without computers. The current day advancement in computer simulation enables one to revise the old statistical concepts.

According to Bose, the photon does not have any intrinsic structure. In quantum electrodynamics, which is integrated into the Standard Model, the photon is still elementary with no known persistent constituents[2]. Could the blackbody radiation (BBR) spectrum be a manifestation of the photon's structure with a few constituents, but without a need for multiple species of elementary quanta? This paper attempts to address this question from the viewpoint of statistical thermodynamics. To make a proper comparison of energy spectrum for "constructed" photons to Planck's law, the number of photons in both models should be the same.

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[2] Due to the uncertainty principle, any elementary particle in the quantum field theory, including a photon, can fluctuate into a variety of short-lived virtual states. If virtual particle interacts with another object, it could expose the photon structure. The existence of such structure has been well established experimentally at high energies [6,7]. Though, the blackbody radiation is observed at low energies where the quantum fluctuations are more difficult to observe. Some researchers have concluded that "from the foundations of quantum electrodynamics the photon should be a dressed, i.e., a composite particle for all times" [8] and discuss a replacement of quantum electrodynamics with "quantum field theory of composite photons". The majority of other bosons in the Standard Model are recognized to be composite.

II. PLANCK'S RADIATION LAW FOR A FIXED NUMBER OF PHOTONS

Frequency is attributed to a photon as a whole, and is not very appropriate for the constituents that will be introduced in the next section. Using energy ε instead of $h\nu$, Planck's law for the unit volume can be rewritten as:

$$u(T,\varepsilon) = \frac{8\pi}{(hc)^3}\frac{\varepsilon^3}{e^{\varepsilon/k_B T}-1}. \tag{3}$$

The corresponding number of photons is distributed with energy as:

$$n(T,\varepsilon) = \frac{u(T,\varepsilon)}{\varepsilon} = \frac{8\pi}{(hc)^3}\frac{\varepsilon^2}{e^{\varepsilon/k_B T}-1}. \tag{4}$$

And the total number of photons in the unit volume at temperature T can be found from integration:

$$N_0 = \int_0^\infty n(T,\varepsilon)d\varepsilon = \frac{8\pi}{(hc)^3}\int_0^\infty \frac{\varepsilon^2 d\varepsilon}{e^{\varepsilon/k_B T}-1}.$$

Let $x = \varepsilon/k_B T$ and take into account that

$$\int_0^\infty \frac{x^2 dx}{e^x-1} = 2\zeta(3) \approx 2.404, \tag{5}$$

where $\zeta(3)$ is the Riemann zeta function, also known as Apéry's constant. This results in

$$N_0 \approx 2.404\frac{8\pi(k_B T)^3}{(hc)^3}$$

with the fixed number of photons, N, distributed by energy as:

$$f(T,\varepsilon) = \frac{N}{N_0}n(T,\varepsilon) \approx \frac{N}{2.404(k_B T)^3}\frac{\varepsilon^2}{e^{\varepsilon/k_B T}-1}. \tag{6}$$

So, the notions of length and volume have been excluded from any considerations herein. (The spatial aspects of BBR could be discussed somewhere else.)

III. PROTO-PARTICLES

The following is assumed:

1. Quantization of energy or existence of "proto-particles" with sole energy ε_z that can share the same state, like Planck's energy quanta. However, unlike Planck's quanta, they are not considered to be separate physical entities that can be observed.
2. Each state contains at least one proto-particle (zero-point energy is equal to unity – no empty states).

A simple Monte-Carlo technique similar to the one used in numerical integration can be deployed to populate an array of N integers and obtain distribution of given shape $y = f(x)$ for those numbers.[3] The same stochastic procedure could be utilized to compute the integral (5) above as well.

Two sets $\{e_i\}$ and $\{m_i\}$ of N random integers can be generated. Each set would form a most probable Boltzmann distribution defined by the exponential function $y = f(x) = e^{-x\varepsilon_z/k_B T}$. The integer would stand for the number of proto-particles in the state. The rounding up makes the spectrum discrete and sets its minimum to unity. Distributions of this kind are seen as a result of underlying microdynamics, but Monte-Carlo simulation provides a fast way of getting specific distribution disregarding microdynamics.

Another option is to generate the sets of integers $\{e_i\}$ and $\{m_i\}$ by a reversible integer lattice gas simulation of an isolated system [5] based on continuation of motion without interactions and detailed balancing in interactions. For a model of BBR, the thermalization (interactions) is happening on cavity walls through emission and absorption. So, the automaton represents an emission and absorption processes. Such an automaton can be interpreted in terms of kinetic theory of gases as well, where redistribution of energy occurs by collisions between gas particles inside a cavity, but the interpretation does not affect the resulting occupation number or energy distributions. The cellular grid, as a framework (substitution to space), enables one to organize the set of states into a certain number of dimensions but does not require a metric to be defined. The evolution leads the cellular system to statistical equilibrium, if it was initialized with "elements of disorder".

Integer lattice gas provides a working model of a statistical system, and in this sense, it is a better reflection of statistical thermodynamics ideas than the Monte Carlo approach. However, the lattice gas requires more computational resources and could have a long relaxation time. Either way, one can produce integer states that will be used as building blocks for the composite structure below.

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[3] To do so, pairs of real pseudorandom numbers (Rx and Ry) can be generated as points in the rectangular region that entirely covers the function graph $y = f(x)$. If Ry falls below $f(Rx)$, the value Rx will be rounded up to the nearest integer and will populate one element in the array of integers. Otherwise, the pair of pseudorandom numbers will be discarded. The cycle is repeated till all elements of the array are filled.

IV. PHOTON STRUCTURE

> "I must look like an ostrich that keeps his head buried in relativistic sand so that he does not have to look the evil quanta in the eye. In reality I am, just like you, convinced that one should look for a substructure, the necessity of which has been cleverly disguised by the current quantum theory through its use of the statistical mold …"
>
> Einstein letter to de Broglie, (as quoted in [9])

Now, a new variable, ε_i, can be introduced by combining integers from the sets $\{e_i\}$ and $\{m_i\}$. By examining statistics for different combinations, it has been found in this study that the sum of both plus the geometric mean,

$$\varepsilon_i = e_i + m_i + \sqrt{e_i m_i}\ , \tag{7}$$

produces a distribution that approaches (6). Figure 1 is for the same number of "photon" combinations, (7), as the number of photons in (6), and for the same temperature in simulated exponential distributions for the sets and function (6). The same units of energy ($\varepsilon_z = 1$) are assumed for both.

The energy quantization for constituents would cause degradation of the energy distribution for composite photons at low temperatures (a quantum freeze-out effect) that would become pronounced at $k_B T / \varepsilon_z < 30$. Such degradation is not foreseen for bosons. To avoid this effect, the computations in the picture are for $k_B T / \varepsilon_z = 600$.

The two independent, random variables in (7) can be understood as two constituents of a photon for which energy can vary. The geometric mean can be seen as rotational or interaction energy between the two. This is reminiscent of mesons' structure in the Standard Model: one quark and one antiquark bound together by the strong interaction. The average energy per photon in the BBR spectrum, $\bar{\varepsilon} \approx 2.7 k_B T$, points to the degrees of freedom from the perspective of the structure ($k_B T$ per degree of freedom for a massless particle). The interaction part comprises about $0.7 k_B T$ of it.

The two constituents, with a quite arbitrarily defined interaction, bring one close to Planck's radiation law over a broad spectral range. The combination of three independent random variables would lead to Wien's empirical formula that was introduced in 1896. With quick experimental progress, a call for reassessment came to Planck in 1900, and he improved Wien's formula. Although, such three components (dimensions) are more relevant for a theory of specific heat.

The first composite photon theory was proposed by de Broglie in 1932 to reconcile photons with Maxwell's electrodynamics. In that search for continuity the photon consisted of two then hypothetical corpuscles: a neutrino and anti-neutrino. Initially the idea had been pursued by many researchers, but it had not found much traction later (see [10] and references therein). This paper represents another search for continuity, now in statistics, but again, points to the structure that is akin to de Broglie's or mesons'.

V. CONCLUSION

Bose-Einstein statistics was introduced first to explain the BBR spectrum. It was a step in evolution from Einstein's light quanta to photons as particles. The further advances in particle physics discovered multiple other bosons in addition to photons. The large portion of all bosons is believed to be constructed from an even number of quarks/antiquarks, while the photon, along with other gauge bosons, is still regarded as an elementary particle.

The motivation for this investigation came from an inability to build a reversible algorithm for an isolated system based on Bose-Einstein statistics, while it can be done for classical statistics. In the effort to explain the BBR spectrum from assumptions of statistical thermodynamics, the author came to the structure that is similar to the structure of some composite bosons in the Standard Model. Non-statistical arguments for photon's structure, [10,8] support the formation of the same kind.

If one accepts the photon structure as a foundation of Planck's law, one may also infer that other fundamental bosons have a similar intrinsic organization and are not elementary. Would there be a need for Bose-Einstein statistics at all?

ACKNOWLEDGEMENTS

The author is thankful to Valeri Golovlev for fruitful, stimulating discussions and critical comments.

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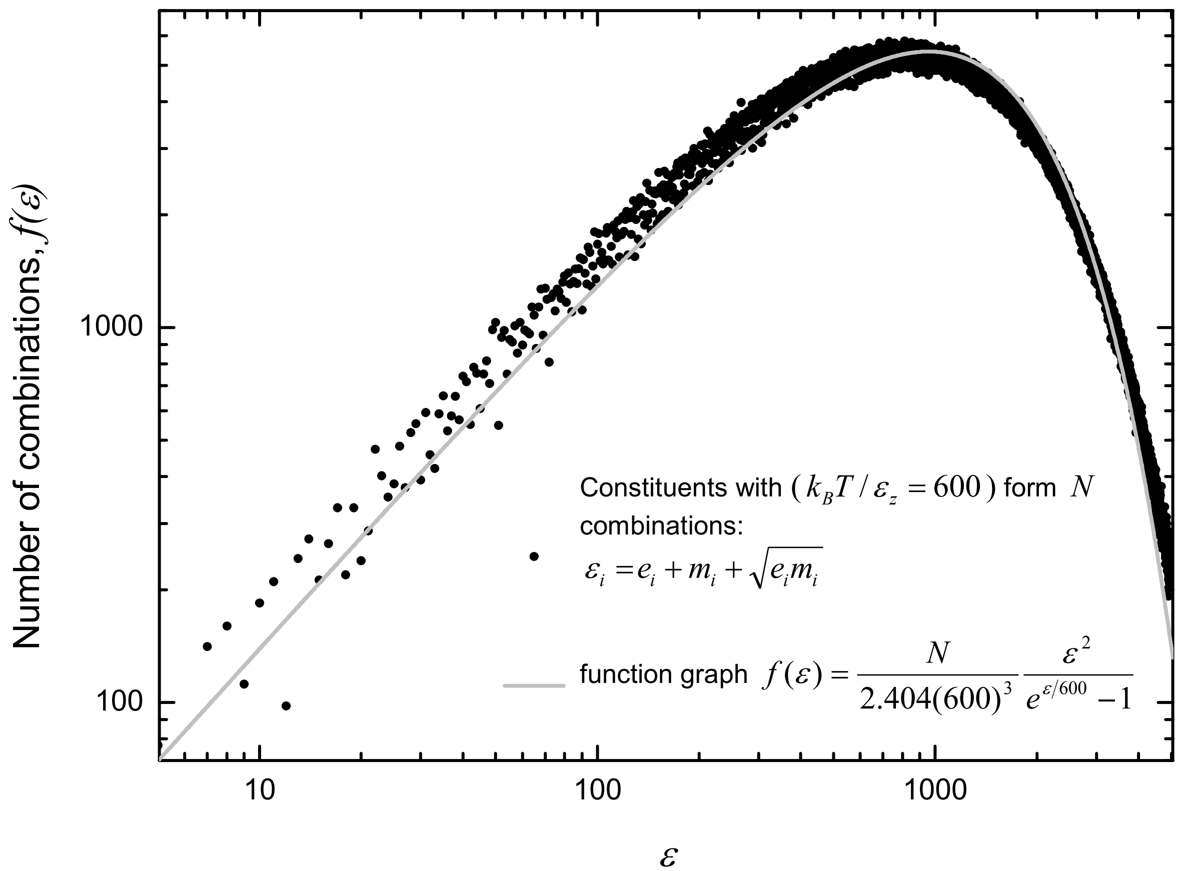

FIG. 1. The number of combinations ($\varepsilon_i = e_i + m_i + \sqrt{e_i m_i}$) in the distribution is N - the same as the number of photons in the function graph. The arrays of constituents used in this simulation are composed of $N \sim 12 \cdot 10^6$ integers each.