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Chance and Superposition in a Quantum Reality World: The Concept of Energy Quantization

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Abstract

Sometimes we come across situations or events where the quantum point of view is presented as a fundamentally unsound theory. Nothing could be further from the truth. Quantum physics is not only the most fruitful scientific theory in history, but also the most resistant and proven in the face of any attempt at refutation. It remains the indispensable basis on which much ongoing research attempts to understand our universe in some depth.

In this article, the importance of quantum physics is highlighted by a case study discussed from the point of view of classical and quantum physics on the study of the frequency dependence of the radiation emitted by a black body in order to arrive at the concept of energy quantization.

Keywords: quantum physics, random, superposition, classical physics, black body, radiation

Introduction

Towards the end of the 19th century, a large number of scientists had succeeded after many successes and failures in making physics an effective tool, capable of explaining almost all known phenomena.

They had managed to bring together such overwhelming theories as Newton's particle interactions, Maxwell's electromagnetic field, thermodynamics and statistical mechanics (1). All of these formed the core of classical physics, and had made it possible to focus the intelligence of order on chaos and randomness. It had succeeded in establishing a set of laws with mathematical expression, which made it possible to explain observed phenomena and make predictions, testable or refutable through experimentation and observation.

The ordered universe could be explained by appealing to two basic concepts: the particle or corpuscle, needed to understand phenomena involving material bodies that move, and the wave, related to phenomena such as acoustic and optical phenomena, where energy is transported through oscillations (2,3).
But there were some mismatches between theoretical and experimental predictions that increased as the 20th century progressed with the discovery of new phenomena (4). Among the main resolution problems detected were: the numerous known atomic line spectra; the recently discovered X-rays; radioactivity; the photoelectric effect and the dependence relationship with the frequency of the radiation emitted by a black body, an ideal object used in physics that is capable of absorbing all the energy that strikes it in the form of radiation.
The latter case will be analysed here, the study of which would lead to the irruption in history of the concept of quantization of energy achieved through the analysis of the theoretical models developed that flagrantly clashed with the empirical evidence (5).

Methodology

The surface of any body with a temperature above absolute zero emits energy in the form of electromagnetic radiation, so that its corresponding spectrum is continuous, with a spectral distribution that depends on the absolute temperature (temperature measured on a scale starting at zero Kelvin, 0K, equivalent to -273.16ºC).
Emission is accompanied by absorption, so that when radiation is incident on the surface of a body, part of it is absorbed by the body itself and part is reflected. Assuming no additional heat transfer phenomena of conduction or convection, when thermal equilibrium is reached, the body remains at a constant temperature, emitting and absorbing the same amount of radiant energy or thermal radiation per unit time and surface area (6). Under these conditions Gustav Kirchoff showed that the quotient between the energy emitted and the fraction of incident energy absorbed constitutes a universal function which is the same for all bodies, regardless of their nature, for each given temperature T and frequency υ.
A black body, in physics, is defined as an ideal body that absorbs all the energy in the form of electromagnetic radiation incident on it, for any frequency and at any temperature, i.e., it does not reflect anything.
A black body at constant temperature T emits radiation according to the universal function established by Kirchoff for all bodies in thermal equilibrium, for each T; hence the function is called the spectral radiance of the black body.
The Sun is a good natural (approximate) example of a black body, which radiates according to this function for a temperature of 5770 K with the spectrum shown in the following figure (blue curve).

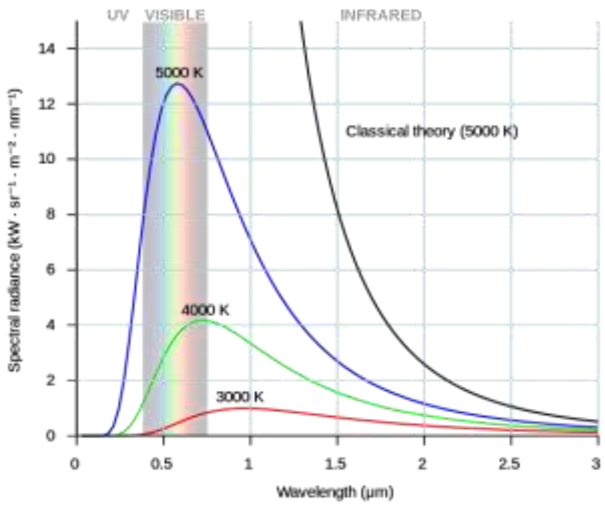

Figure 1. Blackbody spectral radiation as a function of wavelength.

An experimental blackbody model could be made in a laboratory using the Kirchoff gap space (figure 2), an empty cavity or gap with walls that are opaque to radiation, so that it cannot pass through them, and which is maintained at a constant absolute temperature (9). Once thermal equilibrium has been reached inside, it is sufficient to make a small hole in the cavity, so small that the radiation coming through it to the outside does not appreciably disturb the equilibrium inside (10). In such a way that the experimental model constructed absorbs, after multiple reflections inside the cavity, all the radiation that falls on it through the small hole made in its wall.

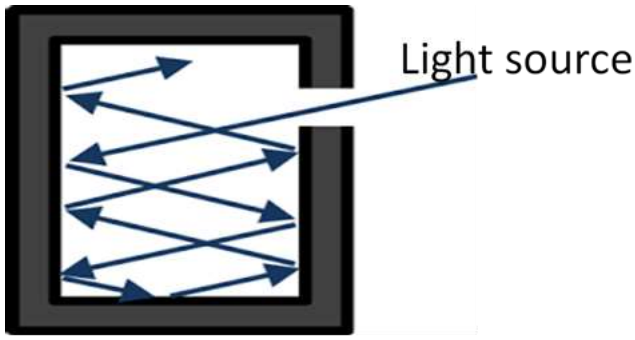

Figure 2. Black body with different energy absorptions

By analysing the radiation emitted through the hole, one can determine that universal function, the spectral radiation of the black body, which is well known experimentally over the entire frequency range (8). Its shape corresponds to the blue line in the graph in figure 1, with an emission maximum that shifts towards longer wavelengths as the temperature decreases (green and red curves).

Different theoretical attempts were made to find the shape of this function, which resulted in different formulas, including that of Wilhem Wien in 1986, published when there was still a lack of experimental information on its behaviour at low frequencies, and it was later proven that the formula failed at these frequencies (11). When analysing the curves obtained with the body at different temperatures, it is evident that this curve depends strongly on the temperature and the material, since each material has its own spectral emissivity curve. Moreover, as the temperature increases, the frequency at which the maximum radiance occurs increases from infrared to opaque red, then to bright red and white.

This result is known as Wien's displacement law:

$$\upsilon_{máx} = \alpha . T \quad (1)$$

Where, ʋmax is the frequency at which the radiance reaches its maximum.

Also, since the speed of electromagnetic waves is the speed of light (c), Wien's law can be expressed as follows:

$$\lambda_{máx} . T = Cte \quad (2)$$

Wien's law is obtained by deriving Planck's law as a function of wavelength and equalling zero:

$$E_{\lambda,b}(\lambda, T) = \frac{C_1}{\lambda^5 \cdot (e^{\frac{C_2}{\lambda \cdot T}} - 1)}$$

$$\frac{d(E_{\lambda,b}(\lambda, T))}{d\lambda} = 0$$

(3 and 4)

Evaluating the derivative it can be determined that the Wien constant is 2897.6 µm.K, therefore:

$$\lambda_{máx} . T = 2897{,}6 \ \mu m . K \quad (5)$$

James Jean and John Strutt (Lord Rayleigh) with the strict application of classical physics, combining statistical mechanics and electromagnetic field theory, arrived at an absurd theoretical formula for spectral radiance (12).

The classical formula made the radiated energy dependent on the frequency (formula 3) in a way that made it grow without limit as the frequency increased, i.e. it led to the ultraviolet catastrophe where an infinite value for the total radiated energy was produced, which is in contradiction with the law of conservation of energy, which is unthinkable. The classical law (Rayleigh-Jean formula) only correctly predicted the experimental results in the very low frequency regions, unlike the formula obtained by Wien.

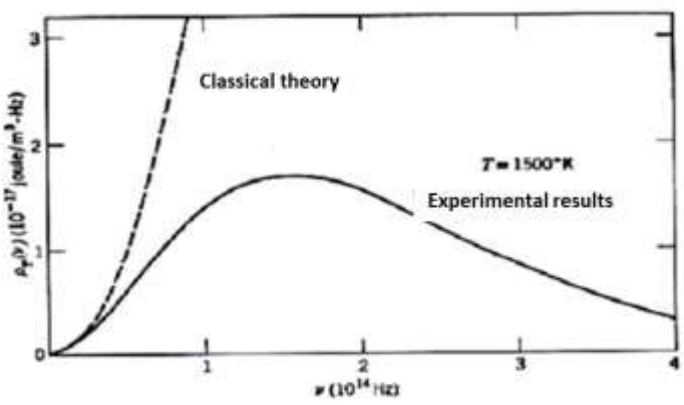

Figure 3. Classical curve predicted by Rayleigh and Jeans versus experimental data

Figure 3 shows the ultraviolet catastrophe phenomenon given by the discrepancy in behaviour of the curve obtained by classical theory (dotted line) compared to the curve obtained with experimental data (solid line) for the energy density in a blackbody cavity (7). This discrepancy is known as the ultraviolet catastrophe.

In 1900, Max Planck obtained a new formula that finally succeeded in fitting the experimental curve over the entire frequency range, explaining that the only way to achieve this had been by resorting to a 'calculational device' of subdividing the energy continuum into small 'elements' of size E=h.ʋ, a discretisation required for the purposes of the combinatorial calculation he developed in his theoretical model (13). In his formula for E, ʋ is the frequency and h is a constant that appeared for the first time in physics and was thereafter called Planck's constant, with dimensions of action, i.e., energy per time, with a value of h=6.626069.10-24 J.s. Planck introduced it as an auxiliary constant, which intervened by subdividing the energy into small 'elements', thus assuming that the energy was not exchanged continuously by the electrons in the walls of the body, assimilated to oscillators, but as if it were 'packed' in energy pulses of value h.ʋ.

Boldly, scientists like Paul Ehrenfest and Albert Einstein would immediately assume the need to elaborate a physics in which the energy of the vibrators considered by Planck was quantized not only when exchanged, but in itself, that is, that the energy of an oscillator could only take values E=N.h.ʋ, where N is an integer, ʋ is the frequency and h is Planck's constant. This hypothesis was a break with classical physics and constituted the first major step towards discontinuity, i.e. the quantization of some of the main physical quantities, which would cease to be continuous and become discrete (14).

Discussion

Physicists have been surprised for some years now by the results of quantum physics research. It was believed that the atom was the smallest thing that existed,

but at the end of the 20th century, subatomic particles were discovered that follow radically different laws, unknown until then.
Research in subatomic physics teaches us that there are apparently incomprehensible movements within the elements of atoms, because they do not obey the laws of classical physics, but other completely different laws. The uncertainty of their state is such that we cannot measure the position of a particle and its motion at the same time (15). One could be talking about the 'freedom' inside the atoms of each material body being real. Hence Heisenberg expounded the so-called 'uncertainty principle', because if an element behaves like a particle, you know its position, but you cannot measure its motion; whereas if you know its velocity, it is because it is behaving like a wave (18). In fact, electromagnetic radiation is made up of quanta of energy that are particles, but at the same time also behave like waves... This has led many to speak of 'quantum randomness', in the sense that sometimes we cannot control the reactions that happen inside atoms, but we know that everything 'works' perfectly (16).
There can be little doubt that the quantum description of nature is essentially mathematical, as it could not be otherwise, since it is a scientific description.
In the quantum context, physical systems possess a capacity that definitely distances them from the classical analogy, since they can occupy a state of superposition with respect to the values of some of their properties. It must be assumed that properties of this type, called contextual, do not in general have values determined prior to their measurement, since, otherwise, it has been shown that the mathematical formalism leads to inconsistency (17). Consequently, the measurement of this class of properties on a physical system provides a result that depends on the specific design of the experiment performed or 'context' of the measurement. Contextual properties include, for example, position, momentum, spin, etc.; however, electric charge would be an example of a non-contextual property (18).
Quantum superpositions configure a world irreconcilable with classical thought and its way of conceiving reality.

Conclusions

Our society today has been reshaped by ICTs in a great change accentuated by the inclusion of quantum physics. Its consequences, beyond the realm of laboratories and universities, scientists and philosophers of science, have transcended into our everyday lives.
Integrated circuits, image analysis algorithms, vehicle control and a long etc., all work by drawing on a quantum root. A large part of what shapes our daily lives in this world exists because we have been able to understand, to a large extent, the laws that govern the results of our interventions on reality when we descend into its smallest dimensions.
The quantification of energy discussed and studied from the point of view of the two theories, classical and quantum, should only be the tip of the iceberg of all the

studies to come in a future where not only the microscopic world will be fully explained by quantum physics, but also the macroscopic one.

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