Original Article

Formation of probabilistic and statistical worldview among students in the process of teaching the topic "Absolute black body radiation" in groups of academic lyceums with in-depth study of physics

Samatov G`ulom Bazabayevich[1] , Sattarkulov Komil Raxmatovich[2] , Obidova Zuhra Nasriddinovna[3] , Nishanova Sarvinoz Baxtiyor qizi[4]

[1]Candidate of physical and mathematical sciences, associate professor Gulistan State University. Uzbekistan. Gulistan city E-mail: gsamatov1950@gmail.ru

[2]Independent researcher, Gulistan State University.Uzbekistan. Gulistan city E-mail: sattarkulov73@mail.ru

[3]Teacher, Gulistan State University. Uzbekistan.Gulistan city

[4]Teacher, Yangier branch of the Tashkent Institute of Chemical Technology
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Abstract

The article analyzes the issues of formation of probabilistic-statistical worldview in students studying quantum physics chapter of academic lyceum of physics. In academic lyceums, there is little time devoted to the subject of quantum physics, the content of the topics is not well covered, in the analysis of the topic, the radiation laws of the absolute black body have a probabilistic character, and in the process of studying this topic, the introduction of probabilistic concepts based on Planck's formula and the study of radiation laws, the content of the subject - The ability of the extraction and enrichment to meet the requirements of the principle of consistency has been studied and discussed.

Keywords: absolute black body, radiation spectrum, radiation energy, spectral density of radiation energy, thermal balance, the ability of bodies to emit, the ability of bodies to absorb light, Stefan-Boltzmann, Wien's laws, the formula of Rayleigh-Jeans and Planck, Planck's constant.

Introduction

It is known from the history of physics that at the end of the 19th century, great achievements in the fields of mechanics, classical electrodynamics, thermodynamics and classical statistical physics made many scientists believe in the achievements of classical physics. By the end of the 19th century, the theoretical and experimental study of the distribution of energy in the thermal radiation spectrum of an absolute black body based on the possibilities of classical physics could not fully solve this problem. [3]

In this article, in the historical sequence, we will focus on the discovery of the law of radiation of the absolute black body by Planck, the creation and development of the science of quantum mechanics as a result of the research carried out on this basis. Studying these topics in the graduation classes of academic lyceums and general secondary schools and continuing to study atomic and nuclear physics in these educational institutions students will form initial concepts about random events and their probability, statistical distributions studied in molecular physics, and based on this, a probabilistic statistical worldview will be formed, students will have an idea about sequence and consistency in explaining physical processes.

Unfortunately, currently, in the physics course curriculums [2] in practice in academic lyceums, only the definition of the absolute black body is given, without the required opinion about the absolute black body. The issues of studying the radiation of an absolute black body are almost not considered, in the textbook [2] the study of quantum physics is also superficially considered, and the quantum theory of light is limited to the illumination of the photo effect laws. Despite the fact that more than a hundred years (1926) have passed since the formation of quantum physics (quantum mechanics) as a science, it is one of the major methodological shortcomings that there is almost no opinion about this science even in academic lyceums where physics is studied in depth. Quantum physics department is taught relatively in-depth in secondary schools of general secondary schools of Russia and Belarus, where physics is taught in depth . In our opinion, it is appropriate to take the study of this subject more seriously in the advanced physics classes of academic lyceums and spend around 16-20 hours studying the quantum physics department, and also allocate a part of this time to teaching problem solving. In physics, we will dwell on the formation of quantum concepts and the research on the formation of quantum physics.

In 1809, in the experiments of physicist-scientist P. Vrevo, if the radiation of two bodies is different, their absorption of different amounts of energy was experimentally confirmed and the existence of a connection between the radiation and absorption of the bodies was proved.

In 1859 G. Kirchhoff discovered the laws of heat radiation, determined the quantitative characteristics of heat radiation, such as the ability of objects to radiate and absorb light.

The Kirchhoff function, which is a universal function of frequency and temperature, representing the ratio of the emissivity of the bodies in the state of thermal equilibrium to the absorption capacity, is included. Emissivity of objects, i.e. radiation energy radiated from a unit surface of a temperature object, at a time and in a unit frequency interval, is defined as follows.

$$\mathrm{E}(\omega,\mathrm{T})=\frac{dW_{light}}{d\omega} \qquad (1)$$

Here, dW_{light}- $\mathrm{T}-$ it is equal to the radiation energy radiated from the unit surface of the body at the temperature, at the same time ω and $\omega+d\omega$ in the frequency interval, and the radiation power from the unit surface of the body in the unit frequency interval. The ability of objects to absorb light is determined as follows.

$$\mathrm{A}(\omega,\mathrm{T})=\frac{dW_{absorbtion}}{d\omega} \qquad (2)$$

In (2) $\mathrm{A}(\omega,\mathrm{T})$ shows how much of the energy of the electromagnetic radiation $dW_{absorbtion}$ falling on the unit surface of the body, at the same time ω and $\omega+d\omega$ in the frequency interval, is absorbed by the body.

In addition to the frequency ω and temperature T, the radiation and absorption abilities of the bodies depend on the chemical composition of the bodies and the condition of the surface.

Kirchhoff's law is expressed as follows.

$$\frac{\mathrm{E}(\omega,\mathrm{T})}{\mathrm{A}(\omega,\mathrm{T})}=\varepsilon(\omega,\mathrm{T}) \qquad (3)$$

$\varepsilon(\omega,\mathrm{T})$- the ratio of the radiation ability of the bodies to the light absorption, does not depend on the material of the bodies, but is determined as a universal function of frequency ω and temperature T.

$\varepsilon(\omega,\mathrm{T})$ - represents the radiation ability of an absolute black body, which depends only on frequency ω and temperature T, when $\mathrm{A}(\omega,\mathrm{T})=1$ is a function.

Based on Kirchhoff's law (3), the radiation laws of an absolute black body were studied, and in 1879, I. Stephan, as a result of experimental research, determined that the integral radiation ability of an absolute black body is proportional to the fourth degree of absolute temperature, L. Boltzmann (1884) based on the second law of thermodynamics, theoretically derives the above formula, but even based on this formula it was not possible to determine the exact form of the Kirchhoff function $\varepsilon(\omega, \mathrm{T})$.

$$\varepsilon(\omega, \mathrm{T}) = \sigma \mathrm{T}^4 \qquad (4)$$

Here: the Stefan–Boltzmann constant is equal to $\sigma = 5{,}67\ 10^{-8}\ \frac{w}{м^2 K^4}$.

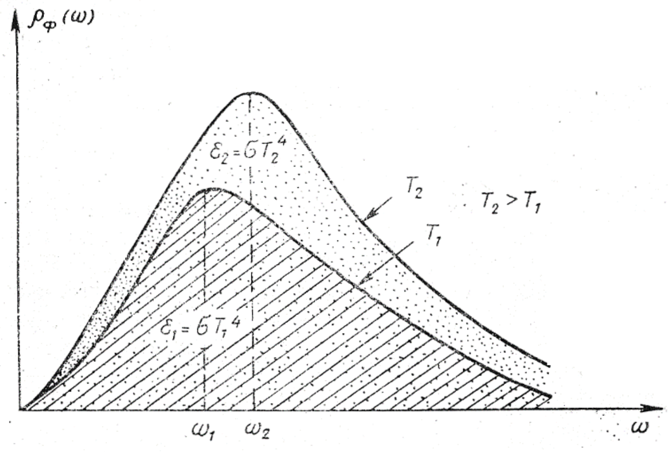


Figure 1.

Dependence of spectral density of radiation on frequency ω. In 1886, Wilhelm Wien analyzed the experimental results on the radiation of an absolute black body and came to the conclusion that the radiation energy corresponding to a unit volume and a unit frequency interval - that is, the spectral density of radiation $\rho_\omega(T)$ - decreases according to the exponential law with the increase of the quantity that determines the ratio of frequency to temperature $\frac{\omega}{\mathrm{T}}$ (Figure 1).

Vin's law, which expresses the dependence of the spectral density of radiation on temperature, is expressed by the following formula.

$$\rho_\omega(T) = A\omega^3 \exp(-B \cdot \omega) \qquad (5)$$

where A, B are constant quantities, this law can fully explain the experimental results at large values of $\frac{\omega}{\mathrm{T}}$.

M. Planck deals with the theory of radiation of an absolute black body and tries to prove Winn's empirical law based on the following considerations in order to determine the frequency distribution of the intensity of electromagnetic radiation of an absolute black body.

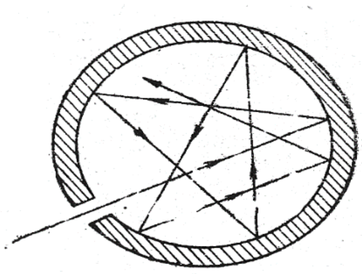
Suppose that several objects heated to different temperatures are placed in a cavity surrounded by ideal reflecting walls. Inside the cavity, even in the case of an absolute vacuum, bodies exchange energy by radiation.

Due to the limited speed of propagation of electromagnetic waves, after a certain time, the inside of the cavity is filled with radiant energy. Experiments show that over time, a stationary state is formed inside the cavity, and the temperature of all bodies inside the cavity becomes equal.

In a stationary state, as much radiation energy is released from the unit surface of the bodies inside the cavity at the same time, the same amount of energy is absorbed.

After a long time, the radiation energy density in the space between the bodies inside the cavity, which depends only on the temperature, reaches a certain constant value, and such radiation is called balanced radiation.

Figure 2. Absolute black body model.



If a sufficiently small slit ($d \approx \lambda$) is opened in the wall of the cavity under consideration, the balance inside the cavity will not be disturbed even if the radiation goes out through it.

Thus, a cavity with a very small slit can be considered as a model of an absolute absorbing body, such a body is called an **absolute black body**. Sometimes, absolute blackbody radiation is also called **balanced radiation**. Based on the laws of thermodynamics, Kirchhoff determined the general law of balanced radiation, that is, $\rho_{\omega}(T)$ the spectral density of radiation energy at the considered temperature does not depend on the nature of the substance of the absolute black body and is proportional to the ratio of the radiation capacity of the absolute black body to the absorption capacity [2].

In optical spectroscopy, radiation that is not in equilibrium with the irradiated body is also considered. Only non-equilibrium radiation depends on the nature of the substance of the irradiated body and can provide information about the irradiated body. If we place this radiant body in a cavity surrounded by a fully reflective wall, it quickly turns into specific, characteristic radiation, heat radiation. In the conversion of non-equilibrium radiation to balanced radiation, "memory loss" occurs many times due to scattering, radiation, and absorption.

In the calculation of balanced radiation energy, heat radiation is considered as electromagnetic field radiation. The electromagnetic field in the cavity is divided into a system of **standing waves** polarized in a certain direction and having different frequencies. From a mathematical point of view, a standing wave is represented by an equation similar to the equation of an oscillating atom or oscillator. Therefore, each standing wave, like an oscillating oscillator, has a corresponding energy $E = kT$. On this basis, the expression of the Rayleigh-Jeans law is obtained.

$$\rho_{\omega}(T) = \frac{\omega^2}{\pi^2 c^3} kT \qquad (6)$$

According to the Rayleigh-Jeans law, which is based on classical concepts, the value of thermal radiation energy in a finite volume tends to an infinite amount. This conclusion contradicts the experimental results, and in the words of P. S. Erenfest, it is called **"Ultraviolet destruction"**.

As noted above, the Rayleigh-Jeans formula (6) can fully explain the experimental results in the range of low frequencies, even if it leads to conclusions inconsistent with the experiments in the interval of complete variation of (i.e. from 0 to ∞).

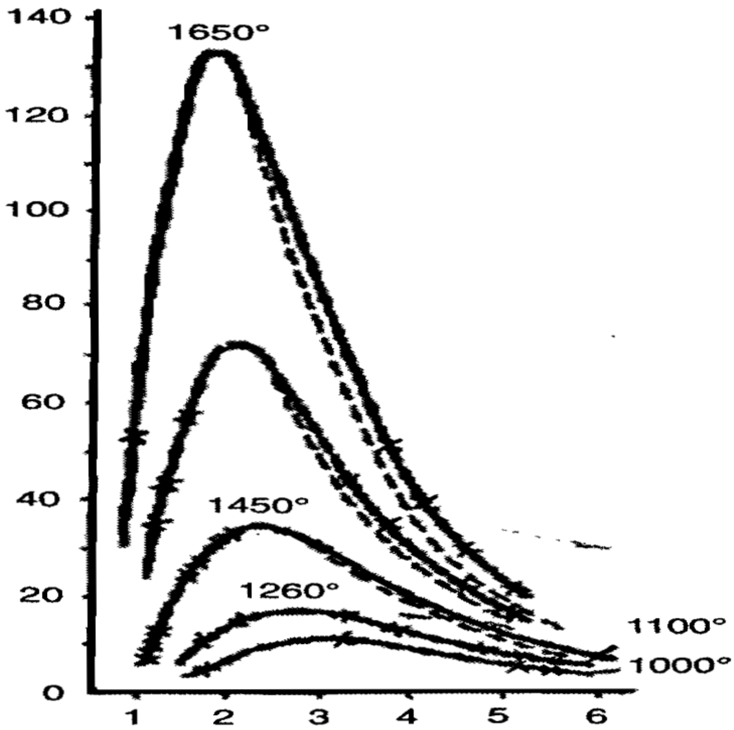
Max Planck conducts research in order to theoretically explain Wien's empirical law and to theoretically study the frequency distribution of absolute blackbody radiation intensity [9].

By Wien, Kirchhoff's formula was presented in a one-variable form, and this formula is called Wien's structural formula.

$$\rho_{\omega} d\omega = \omega^3 F\left(\frac{\omega}{\mathrm{T}}\right) d\omega \qquad (7)$$

Winn's structural formula T is also called the formula for determining the radiation energy density per unit frequency interval of an absolute black body with temperature.

If we express the spectral density $\rho_\omega(T)$ of absolute blackbody radiation energy by λ wavelength and determine the wavelength λ_M corresponding to the maximum of the spectral density of energy, we determine Vin's shift law, which indicates the shift of the maximum of the spectral density of energy with a change in temperature T from (3.2.7).



$$\lambda_M \mathrm{T} = const \qquad (8)$$

From the expression (8), the wavelength corresponding to the maximum value λ_M of the spectral density of the radiation energy in the balanced radiation of an absolute black body is determined to be inversely proportional to the thermodynamic temperature T, and Kirchhoff's second problem is partially solved. Win's formula correctly explains the part of the spectral density of absolute blackbody radiation corresponding to high frequencies (small wavelengths), but does not explain the part corresponding to small frequencies (long wavelengths).

$\rho_\omega(\mathrm{T})$

$\lambda(MKM)$

Figure 3. The appearance of the absolute black body radiation spectrum at different temperatures.

In short, the formulas for the spectral density $\rho_\omega(\mathrm{T})$ of absolute blackbody radiation obtained in the framework of classical physics show the frequency (wavelength) dependence curve (Fig. 3) in two limiting cases, in the low-frequency (long-wavelength) field (Rayleigh- Jeans formula) and in the high frequency (small wavelength) field (Win formula) correctly explains.

In order to fully explain the frequency (wavelength) dependence curve of the spectral density $\rho_\omega(\mathrm{T})$ of the absolute black body (Fig. 3), it was found that it is necessary to introduce new ideas that are fundamentally different from the ideas of classical physics.

Planck explains that the problem of absolute black body radiation can be solved by introducing a new idea that is fundamentally contrary to classical physics. In order to solve this problem, he determined the mechanism that creates the equilibrium of thermal radiation based on a concept more similar to the atomic model, that is, using the model of oscillators that oscillate around the equilibrium state and interact with radiation. This idea played a key role in solving the problem, even though it was not like the atomic structure.

In the theoretical determination and justification of the spectral density of absolute blackbody radiation, Planck introduced the hypothesis that the energy of oscillators can take discrete values.

The radiation energy absorbed or emitted during the transition of oscillators from one state to another is considered to be quantized, i.e., it takes definite, finite values.

When calculating the average value $\overline{\mathrm{E}}$ of the energy of the Planck T temperature system, based on the discreteness of the energy spectrum, he assumed that the energy distribution of the number of oscillators corresponds to the Boltzmann distribution. Based on the Boltzmann distribution, the following expression is obtained for the average energy $\overline{\mathrm{E}}$.

$$\overline{E} = \frac{E_1}{\exp(\alpha E_1) - 1} \qquad (9)$$

Planck's formula is derived from (9) using the formula $\overline{\mathrm{E}}$ connecting the spectral density of radiation with $\rho_\omega(\mathrm{T})$ and $E_1 = \hbar\omega$.

$$\rho_\omega(\mathrm{T}) = \frac{\hbar\omega^3}{\pi^2 c^3} \frac{1}{\exp\left(\frac{\hbar\omega}{k\mathrm{T}}\right) - 1} \qquad (10)$$

From Planck's formula, all formulas and laws of heat radiation of an absolute black body, i.e. Rayleigh-Jeans formula, Wien's formula, Stefan-Boltzmann laws are derived and proved.

In the area of low frequencies and high temperatures, i.e. $\frac{\hbar\omega}{k\mathrm{T}} << 1$ when the condition is met, the Rayleigh-Jeans formula is obtained, in the area of high frequencies and low temperatures, i.e. $\frac{\hbar\omega}{k\mathrm{T}} >> 1$ when the condition is met, the Vin formula is obtained.

Using Planck's formula, the value of the constant σ in the Stefan-Boltzmann law for an absolute blackbody is also calculated.

$$\sigma = \frac{\pi^2 \kappa^4}{15\hbar^3 c^3} = 7{,}56.10^{-16} \frac{ж}{м^3 К^4}$$

In a similar way, the constant b in Winn's displacement law can be calculated exactly.

The most important aspect of Planck's hypothesis is that the oscillator is the change in the energy of atoms, which is not continuous, as always assumed in classical physics, but multiple, discrete occurrences of energy.

Before Planck, a similar idea was expressed by Boltzmann in the form of the opinion that "it is impossible to create a correct theory of statistical thermodynamics without introducing previously unknown elements of discreteness into the radiation process" [9].

This idea of Boltzmann was of great help in creating a great discovery for Planck, and he applied the idea of discreteness taken from the field of statistical physics to the field of the interaction of the radiation field with matter.

Planck applied the laws of thermodynamics and classical electrodynamics, considering heat radiation to be the result of radiation and absorption of electromagnetic waves in matter, and further developed Boltzmann's ideas.

Planck, while determining the spectral distribution of balanced radiation energy in equilibrium with matter at a certain temperature, modeled matter as a set of harmonic oscillators (oscillators) of various frequencies, looked for the maximum entropy of the system, and on this basis proved Vin's formula for the spectral density of radiation energy.

We can consider Planck's work on determining the radiation laws of an absolute black body, the application of thermodynamics and classical statistical physics to the study of thermal radiation of bodies, and the preliminary results showing that radiation and light absorption processes obey statistical laws [7,8].

It is necessary to inculcate these conclusions in the minds of students and emphasize that along with these dynamic laws, statistical laws are also one of the bases confirming that they are one of the important laws of nature, that the main idea (idea) is the introduction of the concept of "quantum of energy" as a discrete portion of energy. A Planck oscillator only has energies multiples of energy $h\nu$, which means that oscillators can only absorb or emit electromagnetic energy in portions. Contrary to the laws of classical electrodynamics, electromagnetic wave radiation and absorption acts occur in a jump-like manner, besides, the quantum of influence, representing the discreteness of energy, is integrally connected with Planck's constant $\hbar$. In Planck's approach, energy discreteness was considered only with respect to matter, that is, the energy of oscillators was quantized, and radiation was considered to propagate continuously as an electromagnetic wave.

It should be noted that since Planck's works focused primarily on the spectral distribution of balanced radiation energy, the issue of radiation or absorption of electromagnetic field energy by separate portions was not considered, and it is appropriate to emphasize this situation.

Planck's hypothesis was a revolutionary step in the development of physics, after Planck's idea, which had an important methodological character, the development of the categories of discreteness and continuity began.

Based on the discussions, the following conclusions are drawn:

1.As a result of studying the subject of absolute blackbody radiation, students can conclude that the Planck oscillator only has energies multiples of the energy $h\nu$, from which it can be concluded that the electromagnetic field can only be partially absorbed or emitted during the interaction of oscillators and electromagnetic fields.

2.Contrary to the laws of classical electrodynamics, the act of radiation and absorption of electromagnetic waves occurs as a jump, which is integrally connected with Planck's constant $\hbar$, the quantum of influence representing the discreteness of energy.

3.On the basis of Planck's idea, the application of the categories of discreteness and continuity in physics begins, and these conclusions, as a result of further theoretical and experimental research, by 1926, led to the creation of the science of quantum mechanics, which is considered the basis of modern physics.

Today, the science of quantum mechanics is the basis of modern physics, and its development provided the creation of today's science of quantum chromodynamics, as well as the theoretical and experimental development of elementary particle physics and nuclear physics. Therefore, one of the most important methodological issues is the inclusion and teaching of the topic "absolute blackbody radiation", which was the initial impetus for the creation of quantum physics, in the physics programs of academic lyceums and general secondary schools.

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