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RADIOACTIVITY IN THE LIGHT OF THE FUNDAMENTAL LAW OF PHYSICS

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Abstract. *One of the fundamental laws of physics is the law of the efficiency of conversion of one kind of energy into another which was formulated in the second half of the 20-th century for the whole region of electromagnetic radiation. On the basis of this law for weak influences (isothermal processes), the whole region of wavelengths of electromagnetic radiation breaks up in two parts, strictly corresponding to the W. Wien region and the Rayleigh-Jeans region, in which efficiency laws are essentially various. Gamma radiation is the most high-energy part of electromagnetic radiation. It is the top frequency boundary for the W. Wien region. The efficiency of conversion of energy for different frequencies of the W. Wien region in the approach of reversible process has been considered. The influence of irreversibility on the conversion of energy in a system for a value of efficiency has been shown. The features of laws of the efficiency of conversion for endergonic and exergonic processes are considered.*

Key words: *α-, β-, γ-radiation, efficiency of conversion, irreversibility of process, Wien region, Bose-Einstein distribution*

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1. The general consideration

The general thermodynamic theory of effects of electromagnetic radiation has been developed in the second half of the 20th century and has given some laws before unknown to physicists [1] – [3]. The laws of the efficiency of conversion of energy for long-wave radiation (the Rayleigh-Jeans region) and short-wave radiation (Wien region) are very different. The efficiency of conversion of radio frequencies and the extra-low frequencies conforms to the Devyatkov law, and the efficiency of conversion of energy in the Wien region conforms to the Weber-Fechner law. These two laws for the Rayleigh-Jeans region and the Wien region are given in Fig. 1, where E_ν is the spectral density of the absorbed power.

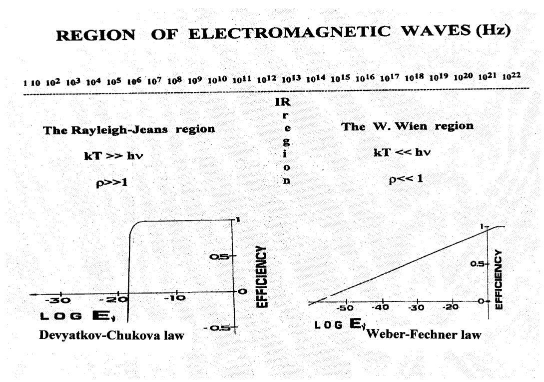

Figure 1. Plan for electromagnetic radiation

The boundary between these two regions lies in the infra-red part of electromagnetic radiation. These two regions give essentially different speeds of the increase of process efficiency as a function of intensity of influence. In the Rayleigh-Jeans region, change of efficiency from 0 to 1 occurs very quickly and demands a small interval of the change of intensity of an external influence. In the Wien region, it needs many orders of intensity for the change of efficiency from 0 to 1. The γ-radiation is the most short-wave electromagnetic radiation, and in this case, the range of the change of efficiency from zero to unit is extremely great.

The division of the whole scale of electromagnetic radiation into two parts has been known to physicists for a long time, since the times when equilibrium thermal radiation was studied (Fig.2).

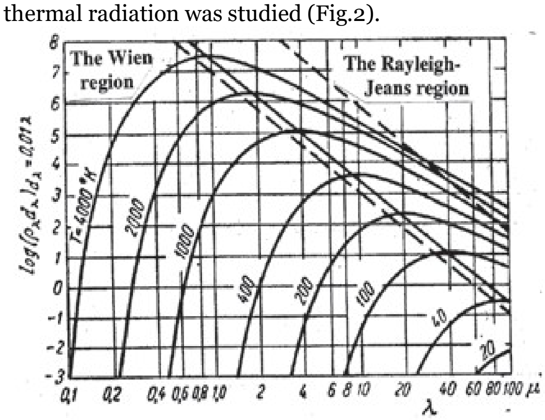

Figure 2. The equilibrium radiation [5]

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W. Wien (1864–1928) generalized the concepts of the absolute temperature and entropy for thermal radiation and formulated two laws for the short-wave wing of equilibrium electromagnetic radiation (Nobel Prize 1911). Lord Rayleigh (1842–1919) described the long-wave wing of thermal radiation (The Rayleigh-Jeans region). Max Planck (1858–1947) introduced the concept of "action quantum", solved the problem of the theoretical description of the full function of thermal radiation (the universal function of Kirchhoff) and deduced the formula for the entropy of thermal radiation (Nobel Prize 1918) [4]. Albert Einstein (1879–1955) introduced a representation about quantum structure of light and explained a photoeffect (Nobel Prize 1921). S. N. Bose (1894–1955) elaborated quantum statistics for particles with integer spin and deduced the Planck law for thermal radiation on this base. The result of their works (Fig. 2) is well known. It completely exhausted the problem of thermodynamics of thermal electromagnetic radiation.

The first step from equilibrium radiation to thermodynamics of nonequilibrium radiation was made by L.D. Landau. Lev Landau (1908–1968) generalized the Planck formula for entropy of thermal radiation for nonequilibrium radiation. Yu.P. Chukova formulated the general law of efficiency of electromagnetic radiation energy conversion into other kinds of energy in irreversible isothermal processes. M.A. Leontovich (1903–1981) calculated the efficiency limit for the direct conversion of sunlight into electric energy. P.T. Landsberg (1923–2010) published the review of works on thermodynamics of nonequilibrium radiation [6].

2. The irreversibility account

Thermodynamics has a rigorous rule to begin a calculation for the thermodynamic limit of efficiency. Fig.1 gives the thermodynamic limit of efficiency η* for the conversion energy of electromagnetic radiation into another kind of energy (electric energy, energy of chemical bonds etc). The thermodynamic limit of efficiency η* is good (obligatory) for reversible processes only, when entropy generation rate $\dot{S}_I$ is equal to zero. All processes on Earth are irreversible and have $\dot{S}_I > 0$. When external influence is weak (low), the entropy generation rate must be calculated according to formula

$$\dot{S}_i = \alpha \dot{W}_a \qquad (1)$$

where $\dot{W}_a$ is the rate of electromagnetic energy absorption, α = const. This linear irreversibility does not change the form of dependence $\eta^* = \eta^*(E_\nu)$, but it gives a shift along the axis. This shift is different in the Wien region and in the Rayleigh-Jeans region (Fig.3), allowing for linear irreversibility of process shifts $\eta^* = \eta^*(E_\nu)$ along different axes. In the Wien region, $\eta^* = \eta^*(E_\nu)$ shifts along the ordinate, but in the Rayleigh-Jeans region, $\eta^* = \eta^*(E_\nu)$ shifts along the abscissa (dashed lines in Fig.3).

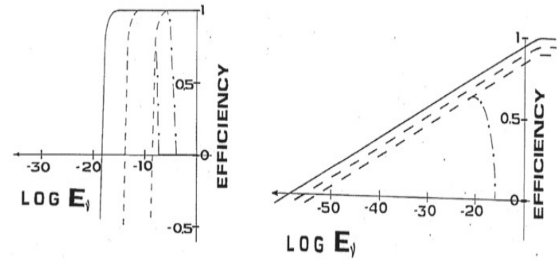

Figure 3. Allowing for irreversibility processes in the Rayleigh-Jeans region (*left*) and in the Wien region (*right*) [1]

It not only is important, but it is interesting because qualitative dependence of a thermodynamic limit is kept in real irreversible processes. It is a very strong argument against those who rest assured that the thermodynamic limit cannot interest experimenters. Absolutely on the contrary, the knowledge of a thermodynamic limit allows the thinking experimenter to make useful practical conclusions.

This correlation of a thermodynamic limit of efficiency and real efficiency has no place (disappears) if entropy generation rate increases super-linearly and corresponds to the formula

$$\dot{S}_i = \alpha \dot{W}_a + \beta \dot{W}_a^n \qquad (2)$$

where β=const and n=const.

In these conditions, η* changes equally in both regions: η* falls up to zero (dash-and-dot lines in Fig.3).

What is the physical sense of the real efficiency of a process? The physical sense is very simple. At the weakest influences, a certain part of the absorbed energy will be transformed into heat, and the other part of the absorbed energy will be transformed to the Helmholtz free energy, leading to its increase. The Helmholtz free energy can be transformed into work of different types; therefore, processes with the increase in the Helmholtz free energy (endergonic processes) draw attention of physicists. In the light of results (Fig. 3) it is obvious that endergonic processes have a beginning and an end. Their end is caused by the increasing part of absorbed energy, which will be transformed into the heat of the system, the isothermal process is ending, and the preconditions for thermal processes are appearing.

Now we will pay attention to one more distinction of the Wien region and the Rayleigh-Jeans region. In the Rayleigh-Jeans region, a frequency change influence on $\eta^* = \eta^*(E_\nu)$ is the same as a change in the linear irreversibility of a process. In the Wien region, the action differs essentially. Frequency decrease (increase of wavelength) leads to a faster growth of efficiency η* in the function of log E_ν (Fig. 4), but the linear increase of irreversibility gives a shift of the full curve $\eta^* = \eta^*(E_\nu)$ along the ordinate towards smaller values (Fig.3, right).

Fig. 4 explains all basic laws which have been found out until today in photobiology. A parameter in the family of curves is the wavelength λ of the absorbed radiation (400nm, 780, 1500 and 3000 nm). The dotted vertical gives the maximum level of sunlight on Earth. Gamma radiation is the most high-energy part of electromagnetic radiation. It is the top frequency boundary for the W. Wien region. Limit efficiency η* for gamma radiation is given by the dot-and-dash line in Fig. 4.

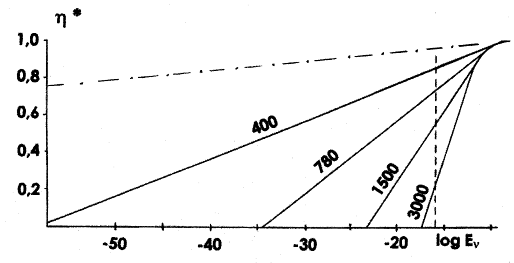

Figure 4. Limit efficiency η* as a function of the spectral density of absorbed radiation E_v (J/cm^2) for different λ (nm)

3. Correlation with experiment

Human vision was studied best of all [7], but there are some problems, some questions [8]. The first problem is connected with Purkyne's effect. In 1823-25, Czech physiologist J.E. Purkyne observed that red things are bright in day but that blue things are bright in the evening. Later, it was shown that the human retina has light sensors of two types: rods and cones. The cones work in the day, but the rods work in the evening. As a consequence, the human eye has two curves of sensitivity (Fig. 5): curve 2 for spectral sensitivity in scotopic vision (night vision) and curve 1 for spectral sensitivity in photopic vision (day vision). The difference between the maximum of these curves is 50 nm. This is a significant value, which is called the Purkyne's shift. Science knows many attempts to understand the reason of this phenomenon's existence. But, for a long time, there was not an exact answer. The thermodynamic answer is simple.

Fig.4 shows that the decrease in illumination shifts the limit for the conversion of long wave irradiation. The efficiency of cones falls up to zero, and the human eye shifts sensitivity to the blue region. Logarithmic dependence of the human eye, known as the Weber-Fechner law [7], is good for almost 20 orders of light exposure. And the attempt of Stevens to cancel this law is absurd from the thermodynamic standpoint [2], [9].

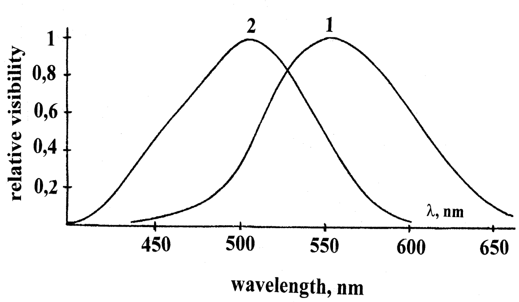

Figure 5. The Purkyne phenomenon

Photomovement of protozoa has three main types: phototaxis (topotaxis), phobotaxis (curve 2, Fig.6) and photokinesis (curve 1, Fig.6) [10], [11]. There are many papers where the logarithmic dependence was observed [12], if the experiment was made at low intensity of light. The logarithmic dependence of the photomovement was observed over an intensity range covering 3-4 orders of magnitude. This dependence was called by experimentalists the Weber-Fechner law, too. If the light intensity is bigger, the dependence of phobotaxis and photokinesis on intensity reaches the maximum and then falls. All of these experimental data demonstrate a good correlation between the thermodynamic theory and the experiment. These results also show that the Purkyne effect exists in the area (sphere) of photomovements and is expressed much more distinctly than in human vision.

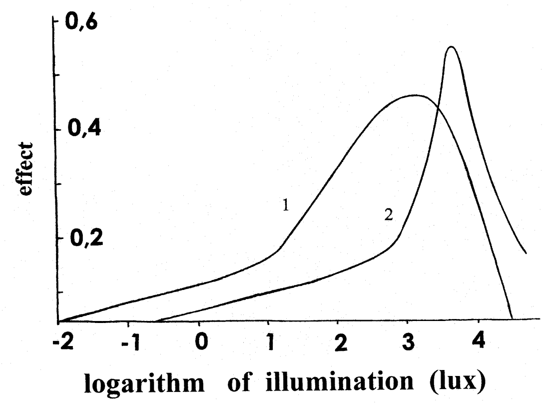

Figure 6. Photomovement of protozoa [10], [11]

The human eye works in the conditions of the change of light exposure more than 10 orders of magnitude ($10^{-26} < E_v < 10^{-16}$ J/cm^2), photomovement of protozoa is observed at the light exposure change by 7 orders of magnitude (from 10^{-23} to 10^{-16} J/cm^2) and photosynthesis of plants at the change of illumination by 3 orders of magnitude (from 10^{-19} to 10^{-16} J/cm^2). A feature of photosynthesis of plants is that it exists only in the conditions of an efficiency maximum when it is impossible to neglect a nonlinear irreversibility.

4. The general conclusion

Everything stated in this paper is connected with endergonic processes, which increase the Helmholtz free energy. Except these processes, exergonic processes with a decrease of the Helmholtz free energy exist.

They take place at the weakest absorption of energy, they are characterised by negative efficiency and are similar to a refrigerator. They are considered theoretically more than enough, but their experimental studying is only beginning and is marked by difficulties of exact measurement of very small doses of the absorbed energy.

On the basis of theoretical (thermodynamic) calculations, it is possible to assert that a transition from endergonic processes to exergonic processes will be accompanied by radical changes in the system. It is rather probable that hazardous-to-health endergonic processes at sign change of η* will appear useful to living systems.

Singular experiments with such results were published in scientific journals. They do not cause trust between the scientific community but they quite correspond to advanced achievements of the thermodynamic theory.

Specificity of efficiency of energy conversion of electromagnetic radiation is defined by a thermodynamic limit and is calculated according to formula

$$\eta^* = 1 - T\,\dot{S}_a / \dot{W}_a \qquad (3)$$

where

$$\dot{W}_a = \int E_\nu d\nu \qquad (4)$$

$$\dot{S}_a = 2\pi k c^{-2} \int \nu^2 \,[(1+\rho)\ln(1+\rho) - \rho \ln\rho]\, d\nu \qquad (5)$$

$$\rho = c^2 E_\nu / 2\pi h \nu^3 \qquad (6)$$

where c is the sun velocity, k is Boltzmann constant, h is Planck constant.

The specificity of efficiency is connected with entropy, which is given by the solid and dot-and-dash line 1 in Fig.7 for Bose-Einstein distribution. $\rho << 1$ (solid part of line 1) is valid for the Wien region, and $\rho >> 1$ is valid for the Rayleigh-Jeans region [13, 14]. The solid line is valid for the Fermi-Dirac distribution. The solid and dash line 2 is valid for the Maxwell-Boltzmann distribution. It means that the logarithmic dependence of efficiency has a place in different systems with many types of excitation.

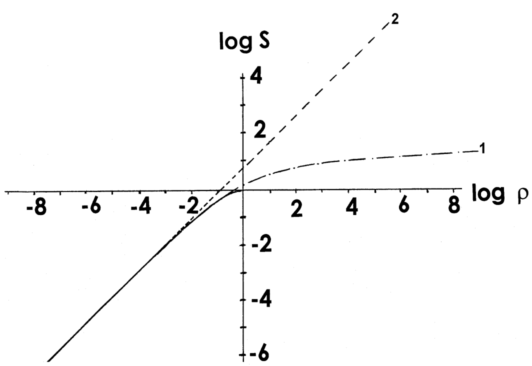

Figure 7. Dependence of entropy S from ρ for Fermi-Dirac distribution (a continuous line), for Bose-Einstein distribution (a continuous line and a dot-and-dash line 1) and Maxwell-Boltzmann distribution (a continuous line and a dotted line 2)

So, the electromagnetic radiation considered in this paper, together with the γ-radiation, conforms to Bose-Einstein statistics. Two other parts of radio-activities (α-radiation and β-radiation) conforms to other statistics. But taking into consideration that for all them $\rho<<1$ in the same way as for γ-radiation, all the results obtained for the Wien region are practically the same; therefore, the acquaintance of different experimenters with the results for the Wien region can be useful and can be used for the interpretation of different experiments with α-radiation, β-radiation and γ-radiation.

References

1. Yu. P. Chukova, *Advances in nonequilibrium thermodynamics of systems under electromagnetic radiation*, Moscow, Russia: Khrizostom, 2001.
2. Ю. П. Чукова, *Закон Вебера – Фехнера*, Москва, Россия: ЗАО МП Гигиена, 2009. (Yu. P. Chukova, *The Weber – Fechner law*, Moscow, Russia: ZAO MP Gigiena, 2009.)
3. Yu. P. Chukova, "Fundamental laws of efficiency of isothermal processes under ionizing and non-ionizing electromagnetic radiation," in *Proc. RAD Conference 2012*, Niš, Serbia, 2012, pp. 351-353.
   Retrieved from:
   http://www.rad-conference.org/helper/download.php?file=../pdf/Proceedings%20RAD%202012.pdf
   Retrieved on: Jan. 22, 2017
4. M. Planck, *The theory of heat radiation*, Philadelphia (PN), USA: P. Blakiston's Son & Co, 1914.
   Retrieved from:
   https://www.gutenberg.org/files/40030/40030-pdf.pdf
   Retrieved on: Dec. 12, 2016
5. В. Г. Левич, *Введение в статистическую физику*, Москва, Россия: ГИТТЛ, 1954. (W. G. Levich, *Introduction to Statistical Physics*, Moscow, Russia: GITTL, 1954.)
6. P. T. Landsberg, G. Tonge, "Thermodynamic energy conversion efficiencies," *J. Appl. Phys.*, vol. 51, no. 7, pp. R1-R20, 1980.
   DOI: 10.1063/1.328187
7. G. T. Fechner, *Elemente der Psychophysik*, Leipzig, Deutschland: Breitkopf und Hartel, 1860. (G. T. Fechner, *Elements of Psychophysics*, Leipzig, Germany: Breitkopf and Hartel, 1860.)
   Retrieved from:
   https://archive.org/stream/elementederpsych001fech#page/n7/mode/2up
   Retrieved on: Dec. 22, 2016
8. Ю. П. Чукова, "О спектральной чувствительности глаза человека," *Доклады АН СССР*, т. 300, но. 2, стр. 504 – 507, 1988. (Yu. P. Chukova, "Spectral sensitivity of the human eye," *Docl. biological science. Proceedings of the Academy of Sciences of the USSR*, vol. 300, pp. 504 – 507, 1988.)
9. S. S. Stevens, "To honor Fechner and repeal his law. A power function, not a log function, describes operating characteristic of a sensory system," *Science*, vol. 133, no. 3446, pp. 80 – 86, Jan. 1961.
   DOI: 10.1126/science.133.3446.80
   PMid: 17769332
10. W. Nultsch, "Der einfluss der lichtes auf die bewegung der cyanophyceen. II Mitteilung: Photokinesis bei *Phormidium autumnale*," *Planta*, vol. 57, no. 6, pp. 613–623, Feb. 1962. (W. Nultsch, "The influence of the light on the movement of the cyanophyceae. II Communication Photokinesis by *Phormidium autumnale*," *Planta*, vol. 57, no. 6, pp. 613–623, Feb. 1962.)
    DOI: 10.1007/BF01930343
11. W. Nultsch, "Der einfluss der lichtes auf die bewegung der cyanophyceen. III Photophobotaxis von *Phormidium Uncinatum*," *Planta*, vol. 58, no. 6, pp. 647–663, Aug. 1962. (W. Nultsch, "The influence of the light on the movement of the cyanophyceae. III Communication Photophobotaxis of *Phormidium Uncinatum*," *Planta*, vol. 58, no. 6, pp. 647–663, Aug. 1962.)
    DOI: 10.1007/BF01914754
12. B. Diehn, G. Tollin, "Phototaxis in euglena. Physical factors determining the rate of phototactic response," *Photochem. Photobiol.*, vol. 5, no. 7, pp. 23–532, Jul. 1966.
    DOI: 10.1111/j.1751-1097.1966.tb09842.x

13. Yu. P. Chukova, “Bose condensation and non thermal processes in living systems under millimeter (MM) radiation,” *Electromagn. Biol. Med.*, vol. 28, no. 1, pp. 41–45, Jul. 2009.
DOI: 10.1080/15368370802708355
PMid: 19337893
14. Ю. П. Чукова, Закон *Девяткова (Эффективность нетеплового преобразования энергии длинноволнового электромагнитного излучения)*, Москва, Россия: Мегаполис, 2006. (Yu. P. Chukova, *The Devyatkov law (Efficiency of nonthermal conversion of energy of long-wave electromagnetic radiation)*, Moscow, Russia: Megapolis, 2006.)