The "Black Body" and the Quantization of the World

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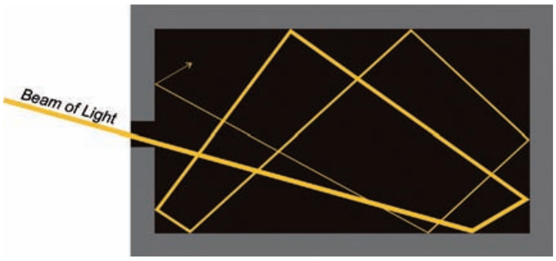
At a temperature above the absolute zero point, each body emits electromagnetic radiation which is referred to as "thermal radiation". Already in 1860, Gustav Kirchhoff realized that for a body which completely absorbs all incident radiation (absorptivity $\alpha = 1$), the spectrum of the emitted thermal radiation is independent of the form and the material of the body, and is only a function of the wavelength and of the temperature [1]. Since the time of Kirchhoff, such a body has been called a "black body".

On the basis of the second law of thermodynamics, Kirchhoff concluded that – in thermal equilibrium – for the same temperature, wavelength and direction, the directional spectral absorptivity is equal to the directional spectral emissivity. The spectral emissivity describes a body's capability to emit thermal radiation. For a black body, the spectral emissivity is thus equal to one for all wavelengths, and no body of the same temperature can emit more thermal radiation than a black body.

After this important discovery of Gustav Kirchhoff, the search for an analytical description of the thermal radiation spectrum of the black body became the most prominent challenge of theoretical physics towards the end of the 19th century.

Soon after the founding of the *Physikalisch-Technische Reichsanstalt (Imperial Physical Technical Institute* – PTR) in 1887, the measurement of the radiation of black bodies became an important task of the laboratory for optics; it was conducted by the scientists Ferdinand Kurlbaum, Otto Lummer, Werner Pringsheim, Heinrich Rubens and Wilhelm Wien.

In 1892, Kurlbaum and Lummer developed the electrical substitution radiometer for the quantitative measurement of electromagnetic radiation, which was an absolute prerequisite for the measurement of thermal radiation. Also for the practical generation of the thermal radiation of a black body, the PTR physicists Wien and Lummer broke new ground by proposing isothermal cavities as radiation sources in 1895. Thus, they acted on an idea which Kirchhoff had already put forward. According to Kirchhoff, the thermal radiation inside an isothermal cavity should exactly correspond to the radiation of a black body. To observe the radiation, the cavity has to be provided with a small aperture. As long as the aperture is very small compared to the surface of the cavity, a light beam falling into the cavity can pass through many reflections on the walls of the cavity and will finally be completely absorbed. Thus, the only radiation that leaves the cavity is the thermal radiation of a black body that has been generated in the cavity.



Picture on this page: "Complete" absorption of a light beam which falls into a black body

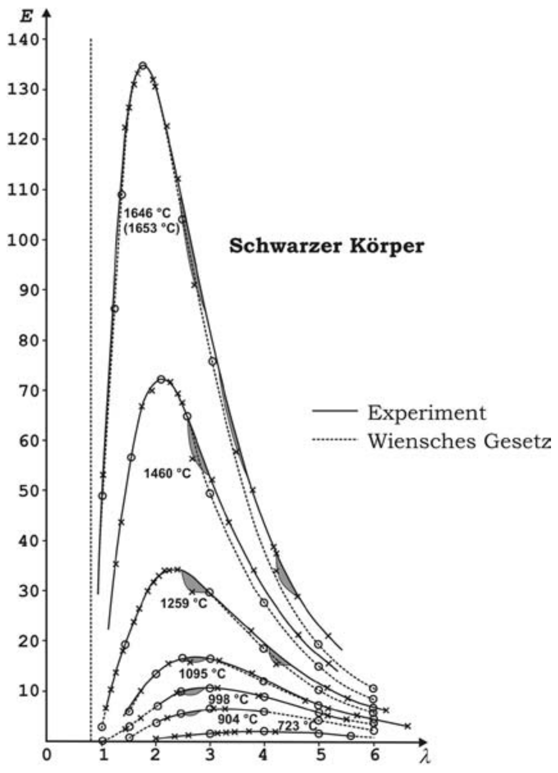
Figure right page, left column: Spectrum of the thermal radiation emitted by a black body, measured by Lummer and Pringsheim in 1900 and compared to Wien's radiation law

Picture right page, right column: High-temperature cavity radiator of PTB which can reach temperatures of 3000 °C. The temperature is measured optically by means of absolutely calibrated radiation detectors.

Initial investigations on these cavity radiators led Wien to the formulation of a radiation law in 1896 which was named after him and which led to the belief for a few years that it would describe thermal radiation correctly [2]. In the following three years, Lummer and Kurlbaum developed an electrically heated cavity radiator which could generate thermal radiation up to 1600 °C. Exact measurements carried out by Lummer and Pringsheim with this radiator showed significant deviations from Wien's radiation law at higher temperatures and greater wavelengths [3]. The broken line in their diagram was calculated according to Wien's radiation law. The continuous line represents the result of the measurements in the spectral range of 1 µm to 6 µm, which increasingly deviate from Wien's radiation law at high temperatures and increasing wavelength.

In 1900, Rubens and Kurlbaum used the *"Reststrahlenmethode" (residual ray method)* in order to be able to demonstrate unambiguously at even greater wavelengths that with rising temperature, deviations of the measurements from Wien's radiation law became more and more obvious [4]. Rubens reported this result personally to Max Planck who was dealing with the theory of black bodies at the *Friedrich-Wilhelms-Universität (Friedrich Wilhelms University)* in Berlin. On the very same day, 7 October 1900, Planck empirically discovered a formulation of the radiation law for the black body which agreed with all measurements carried out by the PTR. On 19 October, he presented this result at a meeting of the *Deutsche Physikalische Gesellschaft (German Physical Society)* following a lecture held by Kurlbaum [5].

In the following two months, Planck succeeded in a theoretical deduction of his equation. For this purpose, he transferred the concept of the harmonic oscillator (which had been introduced by Heinrich Hertz in 1889 to describe the emission and absorption of electromagnetic radiation) to the thermal radiation of the black body. In an "act



of desperation”, Planck only allowed certain (discrete) states of energy. On 14 December 1900, he presented his deduction of the radiation law at the meeting of the *Deutsche Physikalische Gesellschaft* in Berlin [6]. Today, this meeting is regarded as the “hour of birth of quantum mechanics”.

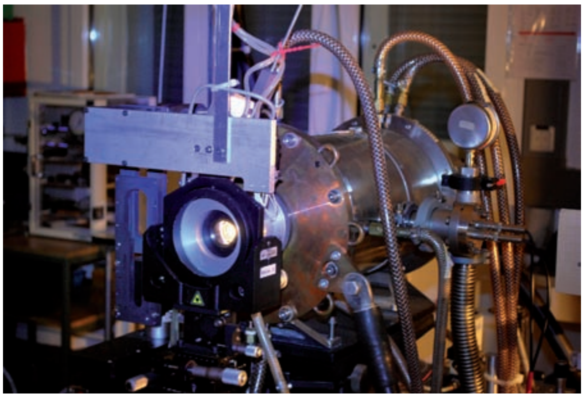
Besides the dependence of the spectral radiance on temperature and wavelength, the thus derived Planck’s radiation law named after him contains also three fundamental constants: the speed of light *c*, the Boltzmann constant *k* and Planck’s constant *h*.

$$L_\lambda = \frac{2hc^2}{\lambda^5} \cdot \frac{1}{\exp\left(\frac{hc}{k\lambda T}\right) - 1}$$

In this formulation of Planck’s radiation law, L_λ describes the spectral radiance of the black body in vacuum. The spectral radiance with the unit W nm^{-1} m^{-2} sr^{-1} is the emitted spectral radiant power normalized to the surface of the radiating body and the solid angle to which the radiation is emitted.

After a comprehensive theoretical understanding of thermal radiation had been achieved, the PTR developed the respective temperature measurement, which today is referred to as “radiation thermometry”, into a precise method of the non-contact temperature measurement in science and technology. For nearly one century, the high-temperature cavity radiator introduced by Lummer and Kurlbaum was the only primary radiation standard for the realization and dissemination of temperature and radiation. It was not until the 1980s that a second primary radiation standard – the electron storage ring – could be developed.

Today, the cavity radiator is still used for the realization and dissemination of the high-temperature scale as well as of radiometric and photometric quantities from the ultraviolet up to the infrared spectral range. Only recently, a cavity radiator has been developed at PTB which even permits radiation measurements to be carried out in the extremely long-wave spectral range of THz radiation (30 µm up to 1500 µm). At PTB, blackbody radiation can nowadays be generated by means of precision cavity radiators at any temperature in a range from –170 °C up to 3000 °C. [7]. For the calibration of radiation thermometers, standard measurement uncertainties of 70 mK are achieved at the freezing point of silver (approx. 962 °C) and 700 mK at 3000 °C, and thus the measurement uncertainty requirements are met which are placed on radiation thermometry as a quick and non-contact method of temperature measurement for modern production monitoring and control.



Today, temperature measurements of the Earth’s surface from outer space and of the Earth’s atmosphere with a very high resolution over long periods of time and over great areas represent a new challenge for temperature measurement on the basis of the black body. They are intended for the precise monitoring of possible climate changes and provide important input data for climate model calculations. But not only for remote sensing of the Earth, but also for industrial process engineering, imaging temperature measurement is becoming more and more important. The bolometer, which was still used by Kurlbaum as an individual detector, is now manufactured lithographically as a sensor array with typically 12,000 to 310,000 single bolometers with a sensor size of 25 µm × 25 µm, and is integrated as a key component in thermographic cameras which are becoming less and less expensive. Measuring facilities are developed and operated at PTB which allow the instrumentations of remote sensing of the Earth and imaging temperature measurement systems to be calibrated with reference to the cavity radiation under application-oriented conditions and thus the measurements performed with a small measurement uncertainty to be traced back to the International Temperature Scale. Thus, the Physikalisch-Technische Bundesanstalt stands for 125 years of continuous work on and with the radiation of the black body. ■

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