Chapter 2
The Problem of Heat Radiation

Abstract This chapter summarizes the problem of heat radiation in the second half of the nineteenth century. For most physicists, this problem amounted to finding the explicit form of the radiation law. In the first phase, experimental research and general thermodynamical arguments imposed some constraints on the form of this law. One of the great conundrums of the final decades of the nineteenth century was to discover a plausible derivation of the exponential term revealed by the experiments. Here, I pay special attention to Wien's research program. Wien combined electromagnetic theory, kinetic theory, and thermodynamics in a very creative—and sometimes opportunist—manner. More importantly, for Wien the black-body problem was a window on the study of more intricate forms of interaction between radiation and matter. Planck's program, as we will see in the next chapters, had a totally different agenda.

Keywords Heat radiation · Black-body · Thermodynamics · Electromagnetism · Wien

2.1 The Origins

In the second half of the nineteenth century, physicists began to be increasingly concerned with the radiations emitted by bodies. In the vast phenomenology of the induced emissions, the so-called heat radiation occupied a sort of privileged position. The reason was that such radiation was considered to be the basis for more complex processes such as fluorescence and phosphorescence. Although heat radiation depends on the temperature of the body and, in general, on its chemical and physical nature, it turned out that its essential features could be represented in a very simple way.

Gustav Robert Kirchhoff (1824–1887) was the first to give a full-fledged theoretical treatment of heat radiation in 1860. By combining thermodynamic arguments and phenomenological considerations, he clarified the general properties of thermal emission and absorption. The most original conceptual tool introduced by Kirchhoff in his research was the notion of an ideal body, "which absorb[s] all the rays that fall upon [it] at infinitesimal density" (Kirchhoff 1860, p. 277). Because no radiation

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is reflected, this object was called a black-body. Later in the same paper, Kirchhoff explained how to experimentally construct a black-body:[1]

> If a cavity is surrounded by bodies at the same temperature and no ray can penetrate these bodies, then each bundle of rays in this cavity possesses the same quality and intensity as though it came from a perfectly black-body at the same temperature, i. e. independent of the particularities and form of the body and constrained by the temperature only. (Kirchhoff 1860, p. 300)

More importantly, Kirchhoff also showed that the ratio between emissive power $e(\lambda, T)$ and absorption power of a body $a(\lambda, T)$ is a universal function of the wavelength and the temperature:[2]

$$\frac{e(\lambda, T)}{a(\lambda, T)} = F(\lambda, T), \tag{2.1}$$

independently of the form of the bodies or the substance they are made of. Kirchhoff's analysis had two important consequences. Firstly, it entailed that each wavelength can be treated individually as far as its thermodynamical properties are concerned: the radiation is an ensemble of independent components of different wavelengths. Secondly, because for a black-body $a(\lambda, T) = 1$, the emissive power of such a body yielded the sought-for universal function. Kirchhoff concluded that "to find this function is a task of the utmost importance" (Kirchhoff 1860, p. 292).[3]

These remarkable accomplishments encouraged further experimental and theoretical research on the properties of the black-body. The experimental investigation benefitted very much from the introduction of the interferometer and the bolometer in the 1880s.[4] A massive collection of precise measurements ranging from the visible to the infrared region and carried out by means of techniques used in the study of optical dispersion and fluorescence allowed for the determination of some general characteristics of the distribution function $F(\lambda, T)$. One of the first properties to be ascertained was the 'displacement' of the maximum of energy. If one plots the wavelength against the energy at a certain temperature, one discovers that the wavelength $\lambda_{\max}$ corresponding to the maximum energy changes with the temperature because the product $\lambda_{\max} T$ is a constant (Crova 1880; Langley 1886a, b).

A second important property, also firmly established by bolometric experiments, was that the irradiated energy decreases toward both extremes of the spectrum, and the decreasing becomes faster toward the violet limit. These two pieces of information suggested that the correct distribution law had a bell-like form typical of the Gaussian or Maxwellian curve. From the analytical standpoint, this entailed that the universal function $F(\lambda, T)$ contained a suitably weighted exponential term. Further information on the distribution function came from the analysis of the total energy irradiated

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[1] On the history of the black-body see also (Darrigol 1992; Kangro 1970; Kuhn 1978).

[2] The emissive power is the quantity of energy emitted by the body in radiation form in time unit at a given wavelength and temperature; the absorption power for the same wavelength and temperature is the fraction of impinging energy absorbed by the body.

[3] On the complex story of Kirchhoff's law and its disputed proof see (Schirrmacher 2003).

[4] On bolometric experiments see (Loettgers 2003; Lombardi 2003).

by a black-body. In 1879, Josef Stefan guessed from experiments that the energy emitted by bodies was proportional to the fourth power of the temperature. In 1884, Ludwig Boltzmann (1844–1906) gave a rigorous derivation of this result (Boltzmann 1884a, b; Stefan 1879).[5] He drew upon the work of Adolfo Bartoli, who had discovered an interesting analogy between a cavity full of radiation and a thermodynamic system.[6] By arranging black and reflecting cavities it was possible to construct a cyclic process in which heat was transmitted from one body to another. The cavity radiation could be handled by the usual methods of thermodynamics. To remain consistent with the second law, one had to assume that radiation exerted a pressure so that a performance of work would compensate for the transfer of heat. Boltzmann realized that by combining this process with the concept of radiation pressure proposed by James Clerk Maxwell (1831–1879) in his electromagnetic theory, he could derive a relation between energy density and temperature.

According to Maxwell, the pressure exerted by an electromagnetic radiation on a surface depends on the density of radiation impinging perpendicularly on the surface. In a cavity, heat rays blaze along any direction, but if we assume the cavity to be a parallelepiped, on average the quantity of energy hitting a selected surface of the cavity perpendicularly is one third of the density. This was nothing but the application of an argument already common in kinetic theory. If the heat radiation produces pressure, it is easy to get a relation, which has the form of an exact differential, between pressure, temperature, and volume variation. By replacing the pressure with the energy density u_λ, Boltzmann found immediately:

$$\int_0^\infty u_\lambda d\lambda = \int_0^\infty F(\lambda, T) d\lambda \propto T^4. \tag{2.2}$$

Together with the earlier experimental insights, the Stefan-Boltzmann law stimulated bolder guesses on the form of the distribution function. For instance, Heinrich Weber (1843-1912) extrapolated from his and others' experimental results an exponential expression for the energy density that satisfied the essential condition of displacement (Weber 1888). More interesting, though, was the theoretical derivation of the Russian physicist Vladimir Michelson. The key idea was to connect the exponential term to some sort of Maxwell's distribution in the radiation field by assuming that heat radiation was produced "by the complete irregularity of the vibrations of [the] atoms." (Michelson 1887, p. 426). Michelson supposed that atoms in solids can vibrate around equilibrium positions. Contrary to the usual theory of solids, though, he did not assume a restoring force: atoms are supposed to move freely within a sphere centered in the equilibrium position, with their trajectory being the composition of rebounds at the boundary of the sphere and erratic influence of the neighbor

[5] The Stefan-Boltzmann law enjoyed almost immediate experimental confirmation; although Heinrich Weber pointed out deviations at higher temperature (Weber 1888), it was found perfectly correct up to 1535 K by the end of the century (Lummer and Pringsheim 1897).

[6] On Bartoli's work on radiant heat see (Carazza and Kragh 1989).

atoms. This peculiar assumption allowed Michelson to introduce equiprobability (of the positions in the sphere and of the directions of motion) and to show that the most common trajectory passes through the center as a diameter.

To this already disputable derivation, Michelson added two further assumptions. Firstly, he assumed that an atom vibrating along a diametrical trajectory gives off radiation whose period depends on the velocity v of the atom and on the radius ρ of the sphere according to the relation $\tau = 4\rho/v$. If the velocities are distributed according to Maxwell's law, one can find the number of atoms giving off radiation of a certain period simply by replacing v with τ in the usual Maxwell distribution.

Secondly, the intensity of the emitted radiation must depend on the number of atoms vibrating with the corresponding period, on a function of the period itself, and on a function of the absolute temperature. Michelson offered no justification for these suppositions. Imposing the validity of the Stefan-Boltzmann law, the energy intensity as a function of the wavelength becomes:

$$I_\lambda d\lambda = BT^{3/2} e^{-\frac{c}{\lambda^2 T}} \lambda^{-6} d\lambda, \tag{2.3}$$

where B, c are constants. Michelson's law fitted the bolometric data reasonably well, although it had an incorrect argument in the exponential term and an incorrect dependence on the wavelength. The important point, however, was the connection between the exponential term and the kinetic theory of gas: this connection appeared to be the most promising way to derive the distribution law.

2.2 Entering Electromagnetism

Heinrich Hertz's (1857–1894) pioneering experiments on the properties of electromagnetic waves boosted further research on heat radiation. Treating thermal radiation as electromagnetic waves enabled physicists to use Maxwell's powerful formalism to understand the nature of heat radiation and to clarify the difficult interaction between light and matter. I discuss extensively the second point in the next sections. Here, I focus upon the relation between the so-called Hertzian waves (in the region of the radio waves) and the heat waves (located in the infrared region). Experimenters used basically the same model deployed to explain optical dispersion and fluorescence: light interacts with matter (atoms or molecules) by co-vibrating with it. In the case of radio wave, it was supposed that rotation was also somehow involved. This model left open the problem of what kind of matter could interact with what kind of light: were Hertzian waves produced by atoms, molecules, or even heavy molecules? Perhaps more importantly, the question of what kind of light produced thermal effects was also on the table. It is important to realize the connection between these experiments and the issue of heat radiation. For most physicists, the problem of deriving the black-body radiation law was tightly related to the problem of understanding the interaction between light and matter down to a very specific experimental description. The very abstract representation provided by the black-body model had to be coupled with a detailed analysis of the constituents of matter and light. Wilhelm Wien (1864–1928), whose research program I discuss in the following section, drew heavily on this tradition, while Planck, meaningfully, ignored it entirely.

One notable example of these experimental studies at the beginning of the 1890s is Viktor Bjerknes's work on the propagation of Hertzian waves in grids and metal lattices. From his research, Bjerkens concluded that while optical phenomena involved the interaction between light and individual molecules, as soon as one moves to the regime of Hertzian waves, the interaction concerns whole groups of molecules: "between the Hertzian and the optical oscillation there must be a transition in which the molecules stop acting together and start doing it individually" (Bjerknes 1893, p. 604). This result cautioned against extending the usual optical formalism to the problem of the interaction of matter and radiation beyond the visible region. Wien elaborated Bjerknes's results on the behavior of light through grids and concluded, on the ground of thermodynamic considerations, that there is an upper limit for the light that can make up heat radiation: "we have to accept that the upper limit of the wavelengths that can be produced by heat lies between the Hertzian oscillations and the infrared rays so far observed" (Wien 1893a, p. 636). For long wavelengths it was difficult to assume resonance phenomena between light and matter (Garbasso and Aschkinass 1894), but in the regime described by Wien, the usual formal machinery of dispersion theory can be used, as was confirmed by Heinrich Rubens (1865–1922) slightly afterwards (Rubens 1894).

These investigations fueled the study on the heat radiation in that they provided a map of the relations between thermal phenomena, optical phenomena, and the new Hertzian waves. The general character of the heat radiation notwithstanding, the physicists coupled the problem of the radiation law together with questions about the theoretical and the experimental details of the interaction between light and matter.

2.3 Wien's Research Program

Planck's program was by no means the sole effort to tackle the problem of heat radiation. It is a historically relevant question to ask preliminarily what characterizes Planck's approach in comparison to similar attempts. An answer to this question will help our investigations in two ways. Firstly, it will show that Planck found many of the concepts, techniques, and formal tools disseminated in the works of the physicists engaged in similar questions. Planck's program was deeply rooted in classical physics. At the same time, and this is the second point, classical physics was made up of many different theoretical traditions: a common disciplinary backdrop such as radiation theory might manifest alternative—and sometimes competing—sets of concepts, priorities, argumentative patterns, and techniques along with different sets of questions. Briefly said, representational, transformational, and explanatory dimensions varied remarkably in the different approaches to the black-body problem. We do not have to take for granted that Planck's final goal was the same as that of his

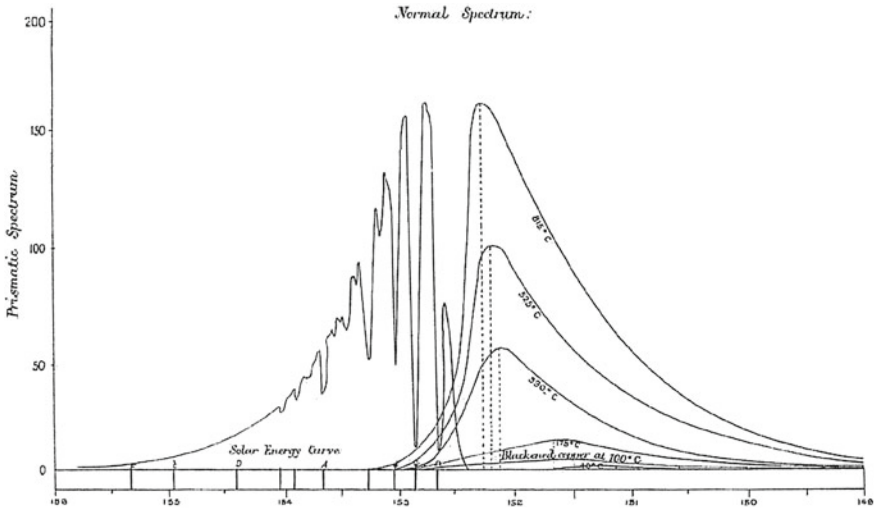

Fig. 2.1 The displacement of the maximum of energy (from Langley's paper)

colleagues, who were working on the same topic. To analyze Planck's competitors means to place Planck's program in the right theoretical tradition.

The best term of comparison for this task is the research program on heat radiation that Wilhelm Wien pursued during the first half of the 1890s. Drawing on the battery of experimental results on the properties of the black-body curve and on the nature of the interaction between light and matter, Wien set for himself a clear goal: to determine the explicit form of the radiation law. This mission had to be accomplished in two steps. The first step consisted of giving a thermodynamic foundation to the still shaky knowledge about the general characteristics of the radiation law. This foundation would also yield the outlines of a thermodynamics of heat radiation. In the second step, one had to supplement the previous considerations with a model of interaction between light and matter that was (1) realistic as far as the experimental knowledge was concerned and (2) able to provide a specific form of the radiation law, in particular the exponential term (Fig. 2.1).

Wien started by giving a thermodynamic argument for the already observed displacement of the maximum of the energy intensity. The basic idea of his approach is that the heat radiation can be treated as a thermodynamic system whose characteristic variables are wavelength, temperature, pressure, volume, and energy. This entails that thermodynamic transformations (temperature variations) can be combined with mechanical one (volume variations) and, more importantly, electrodynamic ones (wavelength variations using the Doppler effect) in order to obtain information on the way in which the radiation changes along with the characteristic variables. Wien assumed three hollow cavities full of radiation like in Fig. 2.2 (Wien 1893b); the picture is from (Wien 1894, p. 134).

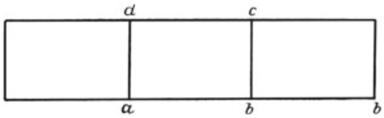

Fig. 2.2 An arrangement of three hollow cavities full of radiation; *ad* and *bc* are movable pistons whose surface diffuses radiation in the cavity; the two outward walls are black-bodies

The partitions *ad* and *bc* between the cavities are movable, and they can also be taken out to let the radiation pass from a cavity to another. By means of this arrangement it becomes possible to study the variation of the spectral energy density. An adiabatic movement of the partitions produces a change in the energy density (volume variation), as well as a wavelength variation due to the Doppler effect. If these two concomitant changes are calculated independently, their ratio turns out to be $u/u_0 = \lambda_0^4/\lambda^4$, where u_0, λ_0 are the value of the energy density and the wavelength, respectively, before the adiabatic process. But the Stefan- Boltzmann law states that $u/u_0 = T_0^4/T^4$; therefore Wien can immediately derive the law:

$$\lambda T = \lambda_0 T_0. \tag{2.4}$$

This general relation holds true for all wavelengths and temperatures: applied to the wavelength with the maximum energy it expresses the 'displacement' effect noticed by the experimenters. The combination of the Stefan-Boltzmann law and the displacement law constrains remarkably the form of the radiation law. For if we know the emissive power $e(\lambda_0)$ as a function of the wavelength, then we can calculate it after the transformations mentioned above by simply replacing the initial wavelength in the argument, that is $e\left(\frac{\lambda T}{T_0}\right)$. This entails that the emissive power (or the energy density or energy intensity) is a function of the product λT. If we now impose the condition that the integral of the emissive power over all wavelengths is proportional to T^4, it turns out that:[7]

$$e(\lambda, T) = \text{const} \cdot T^5 F(\lambda T) = \frac{\text{const}}{\lambda^5} F(\lambda T). \tag{2.5}$$

The following year, Wien furthered his analysis of the heat radiation by establishing an analogy with kinetic theory. In the experimental investigations, the temperature of the radiation was customarily reduced to the temperature of the source, usually a solid body. However, Wien noticed that if a cavity full of radiation is a genuine thermal system, it must be possible to assign a temperature, and even an entropy, to it. To do this, the black-body comes in handy as an ideal thermometer. Here, for the first time, Kirchhoff's ideal black-body is defined in terms of the state of thermal equilibrium: "the radiation of a black-body is henceforth the state of stable equilibrium into which any radiation of different property will transform *autonomously*" (Wien

[7] See (Wien 1894, pp. 158–159); see also (Wien 1909, p. 298).

1894, p. 133). For the black-body radiation, all components (at different wavelength, polarization state, and direction of propagation) have the same temperature, although the energy density differs. The uniformity of the temperature, Wien noticed, derives from the fact that "these components are independent from one another, because we can produce a radiation that contains only one component." This suggests that a cavity radiation is analogous to a mixture of gases of dissimilar chemical species. In an arbitrary state, these components have different temperatures and different energies: the black-body state is reached when the temperature becomes the same for all components and the energy density assumes the simple form required by Kirchhoff's law. To describe how energy can possibly pass from one wavelength to another, the methods of thermodynamics are not enough, and one must introduce an assumption on the microscopic mechanism of interaction.

At this stage, however, Wien is interested in the concept of temperature. Using the black-body radiation as a thermometer, he defines the temperature of a component in an arbitrary radiation state as the temperature that the same component of a black-body radiation would have if it had the same energy density. This definition of temperature is perfectly unequivocal because the black-body radiation curves do not intersect each other, and therefore two different values of the energy density must necessarily correspond to different temperatures.

In the second part of the paper, Wien comes back to electromagnetism: using Maxwell's equations, it is possible to better understand the essence of the cavity radiation. Interestingly, Wien deploys—and it is the first time ever— Hertz's spherical solutions of Maxwell's equations, which were to become Planck's starting point. By means of Hertz's solutions, Wien calculates the Poynting vector and then makes a more accurate evaluation of the work performed by volume increase. But it is the microscopic consequences that interest Wien most. The individual oscillations are perfectly compatible with the laws of mechanics; therefore, if we were able to act on them singularly with a suitable mirror, we could produce violations of the second law of thermodynamics: one can construct an electromagnetic version of Maxwell's Demon.[8] Wien is not afraid of accepting the analogy with kinetic theory until the last consequence: "just as the second principle holds only so long as one can consider the motion of the molecules merely as a whole, thus it ceases to be valid as soon as one can act upon the individual oscillations generated by the heat" (Wien 1894, p. 151).

Finally, Wien introduces the concept of entropy. In thermodynamics, temperature is defined as the integrating denominator of the quantity of heat. Drawing on his previous work, Wien evaluates the variation of the heat content in case of an expansion of the cavity volume. According to the first principle of thermodynamics, such variation is the sum of the change of the internal energy and the external work. Both quantities can be expressed in terms of the energy density. Applying the formal condition for an integrating denominator, Wien finds a relation between temperature and energy density that, unsurprisingly, coincides with the Stefan-Boltzmann law. Dividing the heat content by the integrating denominator, Wien determines the entropy of the

[8]On Maxwell's Demon see Sect. 3.2.2.

radiation $S = S_0 + \frac{4dl}{3\sigma}u^{3/4}$, where dl is the displacement of the partition and σ the constant of the Stefan-Boltzmann law.

At this point, it might be useful to recall Wien's conception of entropy. At the beginning of the 1890s, Wien was particularly impressed by the implications of the work of J. H. Poynting, according to whom one can ascribe to energy quantities that are commonly associated with matter such as localization and motion. We can talk about a flux of energy in the same sense as we talk about a flux of matter. To Wien, this view suggested a possible reconciliation of the two laws of thermodynamics. Indeed, contrary to what happens in the dynamics of fluids, energy has a privileged 'direction'. The entropy principle, in other words, establishes an intrinsic law determining how energy moves in space: "one can express this principle by saying that, given an uneven distribution of its density, the energy moves always so to eliminate this difference" (Wien 1892, p. 724). This interpretation of the concept of entropy strengthens the relation with the principle of least action that Boltzmann and Rudolf Clausius had already stressed in the 1870s (Boltzmann 1866; Clausius 1871). If we confine ourselves to periodic motion, it is possible to show that the requirement that temperature be an integrating denominator for the heat content is equivalent to the Hamilton principle. Wien's conclusion was that:

> [O]ne can apply the entropy principle with certainty only to periodic motions or to motions such that the actual trajectories can be represented by mean values referring to closed trajectories. It is still presupposed that the motion of energy occurs in order to balance out the integrating denominator T. (Wien 1892, p. 726)

The entropy of the radiation is the energy guiding function and depends on macroscopic quantities only. Wien's concepts of entropy and temperature were the best thermodynamics could get without microscopic assumptions. But it was still insufficient to obtain a complete form of the radiation law. In the final pages of the paper, he came back to the analogy with the gas, searching for clues to the solution of the problem:

> When a radiation of a simple color transforms itself into a radiation of mixed colors, the entropy increases and this increase represents a compensation for the possible work obtainable. There is a complete analogy with the entropy increase of a mixture of separate gases. Also in gases the entropy of the mixture is equal to the sum of the entropies of the individual gases as though they were alone in the container. But an irreconcilable difference lies in the fact that the diversities of the gases allow different values of entropy even at the same temperature, while here we have to do with energy that changes the entropy value only through differences in temperature. (Wien 1894, p. 160)

Defining the black-body radiation as the equilibrium state suggested a fairly natural continuation of the argument: supplementing thermodynamic considerations with kinetic-like assumptions to arrive at the radiation law. This was the most obvious way to get the exponential term as Michelson had demonstrated. In 1896, Wien followed precisely this route to complete his program. Here, he puts forward a more general reason why additional microscopic hypotheses of kinetic type were necessary. A purely electromagnetic derivation of the radiation law would call for a mechanism of redistribution of the energies over different wavelengths without performing work or absorbing energy. But, Wien states, "there is at the moment no physical process through which the above mentioned transformation of the colors takes place in a natural way" (Wien 1896, p. 662). For this reason, the radiation law had to be derived by patching experimental information and kinetic hypotheses.

Admittedly, Wien's argument is not much better than Michelson's. He is only more careful about the hypotheses and the general thermodynamic constraints, but the fundamental idea remains the same. He assumes that the wavelength of the radiation emitted by a molecule is a function of its velocity and that the intensity of the radiation at a certain wavelength depends on the number of molecules with the corresponding velocity.[9] In this way one can transform Maxwell's distribution into a distribution over the wavelengths: $u_\lambda d\lambda = F(\lambda)e^{-\frac{f(\lambda)}{T}}d\lambda$. The displacement law and the Stefan-Boltzmann law help determine further the unknown functions. From the former it follows that the energy density must depend on the product λT, and from the latter that it must contain the term λ^{-5}. Putting together these two pieces of information, Wien obtains:

$$u_\lambda d\lambda = \frac{c_1}{\lambda^5} e^{-\frac{c_2}{\lambda T}} d\lambda, \tag{2.6}$$

where c_1, c_2 are two universal constants. This is the longed-for radiation law. Around the same time, Friedrich Paschen arrived at a similar formula by working on the experimental data only (Paschen 1896; paschen 1897). Wien was in contact with Paschen and referred to his law in the paper. More importantly, he was thereby informed that this law fitted very well the experimental results, at least within the range of temperature and wavelength covered by the experimenters. With the derivation of a satisfactory radiation law, Wien's program was finally complete. The apparently shaky derivation was not a big problem: strange as the assumptions could seem, they were rooted in the physical knowledge on the nature of the phenomenon. The study of optical dispersion and fluorescence supported the idea that the radiation emitted by the molecules depended on their velocity, while it was reasonable to think that the intensity depended on their number. For a gas and radiation at relatively short wavelength, the application of Maxwell's distribution was again a natural choice. It was therefore in the microscopic details of the light-matter interaction that Wien looked for the additional hypotheses to supplement the thermodynamic framework.

2.4 Concluding Remarks on the Problem of Heat Radiation

To sum up, when Planck started his own research program, the problem of heat radiation was defined within a framework that comprised the following elements. First, there were some general thermodynamic laws that set many of the essential formal properties of the radiation law. Second, other properties, for instance the presence of an exponential term, followed from the analysis of a huge collection

[9]Contrary to Michelson, who had applied his argument to solids, Wien considers only gases because for gases the assumptions were more justifiable.

of experimental data; in addition, these experiments also gave hints on the nature of heat radiation and on the mechanism of interaction between light and matter. The problem of heat radiation was seen as the paradigmatic example of the general question of light-matter interaction: the extreme simplicity of the phenomena made this case the ideal benchmark for an analysis generalizable to more complex cases, such as optical dispersion and fluorescence, that depended instead on the physical features of the bodies (Rubens 1900). The crucial point here is that the simplicity of heat radiation was not a reason to abstain from conjectures on the microscopic nature of the light-matter interaction, as Wien's program demonstrates. Quite the contrary, physicists were trying to make heat radiation the key to treat all instances of light-matter interaction, and to do that, they had to conceive a theory as realistically as possible.

Wien systematically developed this program to its ultimate conclusion. His main aim was to obtain a radiation function, and to achieve that he combined several resources. He used techniques and argumentative patterns both from thermodynamics and from kinetic theory and electromagnetism. The exponential factor suggested a relation with Maxwell's kinetic methods, which in turn led to a certain representation of the microscopic processes of radiation. For Wien, all these ingredients were the representational and the transformational dimensions to be combined into the explanatory dimension of his program. While to Planck, as we will see later on, the generality of heat radiation justified a non-committal attitude toward the microscopic mechanism of production and transformation of the radiation, for Wien the problem was inextricably intertwined with the elaboration of a realistic model. Some years later, he reiterated this point by criticizing Planck's resonators because they "do not change the spectral composition of the radiation and therefore they cannot represent *a model of a radiating body*" (Wien 1909, p. 302, italics added).

The historical question that we must bear in mind while discussing Planck's theory is now to what extent, if any, this criticism actually reveals a failure in Planck's original program. It is doubtlessly true that Planck's arsenal of concepts and techniques partially overlaps Wien's, such that the temptation is strong to ascribe to both identical goals. Planck, however, inscribed his work within a completely different epistemic story, which led him to a very different approach.

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