Subject:
As a university student one gets to know two classes of light sources, that
differ in their mode of operation. To the first class belong glowing bodies,
the sun and the yellowish-white flame of candles. To the second belong
spectral lamps, lasers, LED’s and colored flames.

Regarding the light sources of the first class, the students learn that black,
hot bodies emit electromagnetic radiation: the thermal or black-body radia-
tion. The spectrum only depends on the temperature of the radiator. The
corresponding function is called Planck’s law.

Regarding the emission of the sources of the second class, the mechanism
seems to be different: The students learn that electrons in atoms, molecules
or in a crystal lattice go from an excited state to a state of less energy and
thereby emit a photon. The frequency of the corresponding light is obtained
from the energy difference between the two states; the intensity depends
on the transition probability. The excitation can be realized in various ways:
electrically, thermally or by optical pumping.

Deficiencies:
The various light sources are discussed on two different conceptual levels:
the sun, the light bulb, the candle flame etc. are treated thermodynamically,
the spectroscopic lamp, the laser and the LED are explained by discussing
processes that go on at the atomic level. Thereby the impression may result
that the emission of the light bulb has nothing to do with atomic physics,
and that the emission of the sodium atoms when strewing table salt in a gas
flame has nothing to do with thermodynamics.

In fact, both types of light sources are based on transitions of a system from
an excited state to a state of lower energy, and in both cases the intensity is
influenced by the laws of thermodynamics.

A justification for choosing two different approaches may be that one often
is only interested in the shape of the spectra. Indeed, the spectrum of a
black body can be obtained by only using arguments of statistical physics.
The microscopic mechanism is irrelevant. On the contrary, thermodynamics
does not help much in obtaining the spectrum of a spectral lamp. Here
atomic physics is needed.

However, if one does not explain how the two patterns of explanation are
related, one can only hope that the students don’t do what normally we ex-
pect from them: ask questions when they do not understand. Such a ques-
tion could be: Why does the sun not have a line spectrum like a hydrogen-
helium spectral lamp?

Origin:
The theories and explanations of black-body radiation and of line spectra
have been developed independently, and they have conserved this inde-
pendence in the teaching of physics until today. Our example also shows
that it is not at all clear what is meant by a “satisfactory explanation”. In one
case we present as an explanation the reduction to a microscopic mecha-
nism, and in the other the description of the process of producing the radiation and the spectral properties of it.

Disposal:

A body whose temperature is not equal to 0 K emits electromagnetic radiation. If its emissivity \( e(f) \) is equal to one at all frequencies (The values of \( e \) are between 0 and 1), the energy flow density \( j_E \) in the frequency interval \( df \) of the radiation is given by Planck’s law:

\[
dj_E = \frac{2\pi h}{c^2} \cdot \frac{f^3}{e \cdot \left( \frac{h}{kT} \right)^4 - 1} df.
\]

Now, the emissivity of a body is for every frequency equal to its absorptance

\( e(f) = a(f) \).

If \( e \) is equal to one for all frequencies, so is also \( a \) and the body is completely opaque; it is black.

If \( e(f) = 1 \) does not hold for every frequency, then Planck’s law becomes:

\[
dj_E = e(f) \cdot \frac{2\pi h}{c^2} \cdot \frac{f^3}{e \cdot \left( \frac{h}{kT} \right)^4 - 1} df \tag{1}
\]

Since for each frequency \( e \) is smaller than or equal to one, the spectral energy flow density for a non-black body is for every \( f \) smaller than or equal to that given by Planck’s formula. An example for such a spectrum is that of the light of colored flames: the bluish light of a methane flame, or the yellow light of a hydrogen flame in which some salt is strewed.

The fact that the spectra of glowing bodies can be described thermodynamically does not mean that the microscopic mechanism of emission is different in principle from that of a spectral lamp. Each photon that leaves an incandescent body is generated in a transition: for the photons of the visible light from an electronic transition, for the long-wave infrared photons from a vibrational or rotational transition. Since in a solid often transitions of all energies are possible, the special case of the Planck emitter is frequently realized. (However, not every macroscopic piece of matter must emit light with a Planck spectrum. A nice experiment that shows it is to heat two adjacent small pieces of different materials with a Bunsen burner; for instance a piece of iron on the one hand and a piece of quartz or sapphire or a white pebble on the other. Whereas the iron piece glows brightly, the quartz, sapphire or pebble does not emit any visible light at all.)

The sun represents a thermal radiator of a particular interest. We know that it consists almost exclusively of hydrogen and helium. Therefore one might expect that its spectrum is a line spectrum similar to that of a hydrogen-helium spectral lamp (which however would be excited thermally instead of electrically). On the other hand we know that sunlight has a continuous spectrum, which is quite close to a Planck spectrum.

How can these two statements be reconciled? The explanation comes from the factor \( e(f) = a(f) \) in equation (1). For a hydrogen gas in the laboratory that is thermally excited this factor is almost exactly equal to zero for almost all frequencies. Except for some frequencies in the ultraviolet domain the gas is completely transparent. Therefore the emission spectrum of the lamp differs greatly from a Planck spectrum. However, the absorptance, and hence the emissivity of the body gets larger when the body gets thicker. When light enters a body and its path within the body is long enough, it will
eventually find a suitable transition. The corresponding path length depends of course on the frequency of the light. In the sun it is at worst a few hundred kilometers. This is much when compared to the size of a spectral lamp, but it is very little when compared with the radius of the sun. A layer of solar matter with a thickness of 10 cm (taken from the area of the photosphere) is fully transparent: It practically does not absorb and thus not emit (in the direction perpendicular to the layer). As the thickness of the layer increases, the absorption, and therefore the emission, also increases. The spectrum is now similar to that of a spectral lamp [1]. When the thickness of the gas layer further increases, there is more and more emission in the region between the spectral lines. A layer with a thickness of 1000 km absorbs every light completely, and thus emits like a black body of a temperature of 6000 K.

But what are the transitions that are responsible for this absorption and emission? Even if we only had a pure hydrogen-helium mixture, and if we neglected the (weak) ionization, we would get total absorption in the visible domain when the layer has reached a thickness of several hundred kilometers. This absorption is due to the width of the spectral lines. But there are more absorption mechanisms: The hydrogen-helium gas is weakly ionized, and the free electrons absorb light. In addition, solar matter also contains all other elements, albeit in low concentration and the absorption of these elements partly lie in the visible spectral range.

Since we know that for our purposes the path length of the light within the sun can be considered as arbitrarily long we need not bother for the question of which of these is the dominant absorption mechanism. This is similar to the well-known experiment, consisting of a box into which a small hole has been cut. The hole is black, whether the interior walls reflect or scatter, whether they are black, white, yellow or blue. The absorption mechanism for the blackness of the hole is irrelevant.


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