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Posted Date: 12 March 2026

doi: 10.20944/preprints202603.0962.v1

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Some Fundamental Modifications to Einstein's Model of the Absorption and Emission of Radiation by Matter

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Abstract

In 1916, A. Einstein developed a model of the absorption and emission of radiation from which he derived M. Planck's radiation law. He postulated light-induced (stimulated) emission, because within the framework of classical physics an oscillator can, depending on the phase difference, both extract energy from the electromagnetic field and transfer energy to it. In a non-coherent field, $\alpha = \beta$ should hold, where α denotes the kinetic constant of absorption and β that of stimulated emission. This assumption is indispensable for deriving the radiation law from his model. In this context, it is problematic that a certain degree of field coherence follows necessarily from his model, which implies that $\alpha \neq \beta$. Moreover, the model cannot readily be generalised to fields of arbitrary coherence. An alternative model for the absorption and emission of radiation by matter is therefore developed here. On the one hand, it is based on the assumption that, within a blackbody, quanta of different energies may recombine freely; on the other hand, it employs the "pairwise interference model of quantum theory" (PIMOQ). The alternative model of the interaction between light and matter allows the radiation law to be derived for thermal equilibrium in a non-coherent field, under which conditions, according to the model, no stimulated emissions occur. It also describes the behaviour of systems with a coherent field (interference experiment, laser). Furthermore, considerations are presented regarding the energy distribution within a blackbody and the explanatory scope of A. Einstein's model in this respect.

Keywords: Planck; Einstein; radiation law; blackbody; photon; light interference; double-slit experiment; laser; coherence; Copenhagen interpretation; energy distribution; state distribution

Introduction

In 1900, M. Planck derived an equation that describes the spectrum of blackbody radiation (and thus also that of idealised stars free of atmosphere) [13]. In contrast to its predecessors, each of which correctly accounted for only a portion of the spectrum, i.e. the relationship between luminous intensity and frequency [11], M. Planck's formulation differed in that its derivation required the assumption that the energy exchanged between a resonator and the electromagnetic field is quantised. The equation therefore marks the beginning of "classical" quantum theory (1900–1925). It is given as follows (ρ: radiant intensity, m_ν: number of photons of frequency ν, h: Planck constant, c: speed of light, k: Boltzmann constant, T: temperature):

$$\rho_\nu = m_\nu h\nu = \frac{8\pi h\nu^3}{c^3}\frac{1}{e^{\frac{h\nu}{kT}} - 1} \qquad (1)$$

In 1909, A. Einstein sharply criticised M. Planck's derivation of Eq. 1 [7], pointing out a serious flaw while simultaneously maintaining the correctness of the equation itself. If the energy quantum ε is large in relation to the mean resonator energy—as is the case, for example, for visible light compared with the resonator energy at 1700° K—the theory would predict very pronounced

doi:10.20944/preprints202603.0962.v1

deviations from the intensity curve given by Eq. 1. However, this is not observed; empirically, Eq. 1 is confirmed with remarkable precision (a circumstance I have referred to as "Einstein's riddle" [18]; it is not the only one). A. Einstein therefore called for an alternative derivation of Planck's radiation law.

In 1900 and 1901, M. Planck described the energy exchange between the electromagnetic field and idealised "monochromatic resonators" (he was not convinced of the existence of molecules), assuming that equal energy quanta $\varepsilon = h\nu$ are exchanged, without making more specific assumptions concerning the absorption and emission of radiation [13,14]. Einstein altered this in 1916 and 1917 [8,9].

One might suppose that, in his derivation of the radiation law, he corrected Planck's "error". However, a careful examination of his model shows that this is not the case [16,18], at least if one assumes that he, too, regarded molecules as resonators. It then follows from the model that highly energetic quanta (energetic in comparison with the mean resonator energy) should occur far more frequently than is actually observed. This may indeed hold quite generally once one assumes that the energy distribution in resonators can be described by the Boltzmann factor

$$n_{E+\Delta E}/n_E = \mathrm{e}^{-\frac{\Delta E}{kT}} \qquad (2)$$

as was done, for example, by S. Bose in 1924 [3] and by R. Feynman in 1963–1965 [12] (**E**: resonator energy; **n**: relative number of resonators).

Figure 1 summarises the results of an earlier study by the present author [18]. Here, **r** denotes the number of energy quanta **R** "stored" in matter, each of energy ε, relative to the number of molecules **N** (**$r = R/N$**). The index **i** refers to the possible energy levels of the molecule or resonator, respectively.

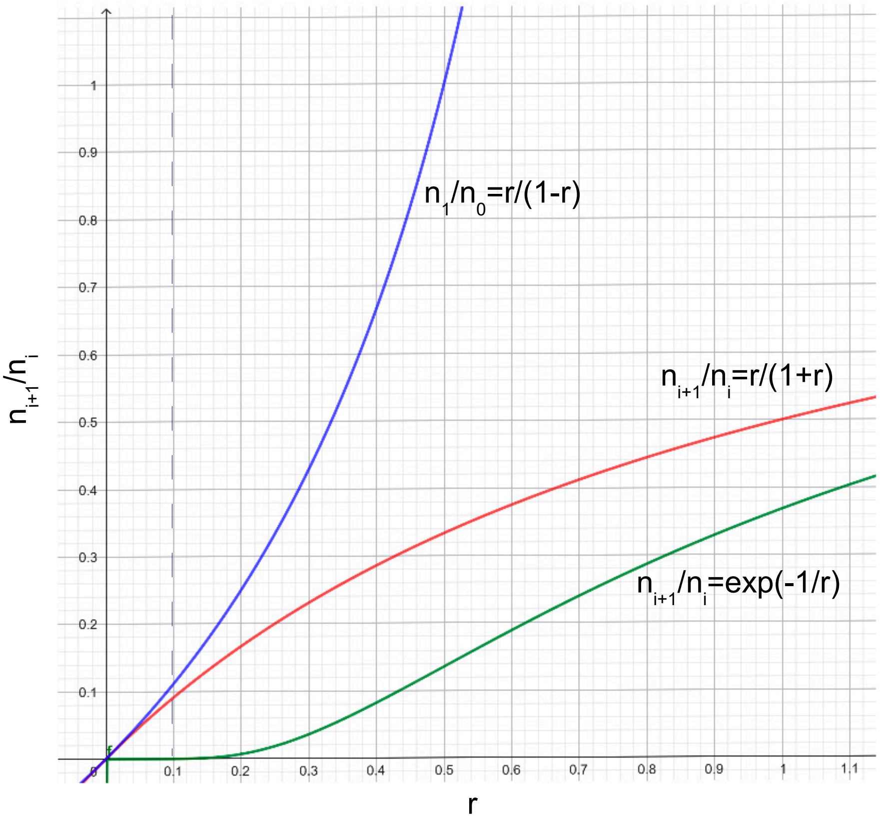

Figure 1. Ratio of the relative frequencies of molecules in adjacent energy states according to three different models. n_i denotes the relative number of molecules in energy state i with energy $i\varepsilon$. r is the number of energy quanta of energy ε relative to the number of molecules N. (The figure was generated using GeoGebra.).

Two-state systems can absorb only a single quantum of a given "colour", i.e. energy ε, and therefore exist either in the ground state (Z_0) or in the excited state (Z_1). The ratio n_1/n_0 is shown in Figure 2 by the blue curve, obtained from the fact that Z_1 contains exactly one quantum, Z_0 none, and under the condition that $n_1 = 1 - n_0$. It is immediately evident that the energy distribution of two-state systems cannot be represented by the Boltzmann factor.

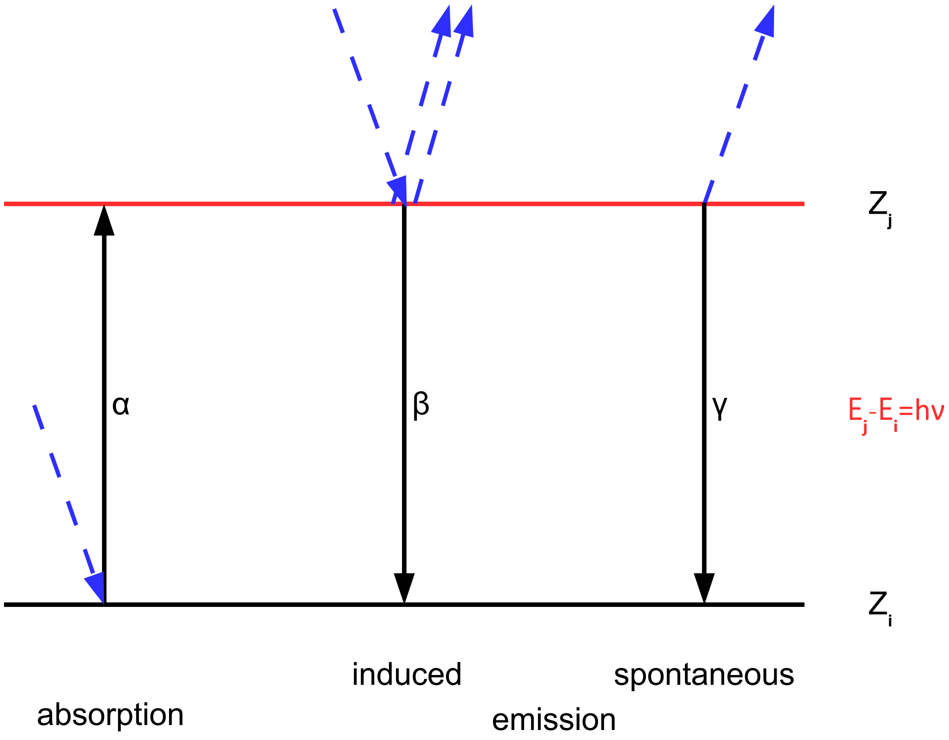

Figure 2. Interaction of light and matter according to A. Einstein (1916) [8]. Two arbitrary energy levels of a molecule are considered.

By contrast, the red curve describes the energy distribution for the monochromatic resonator in A. Einstein's model, if one assumes that "his" molecules are indeed to be interpreted as such resonators. This is not entirely clear. He writes: "*Each molecule shall be capable only of a discrete series* Z_1, Z_2, *etc., of states with energy values* ε_1, ε_2, *etc.*" Whether these states Z_i satisfy $i \in \mathbb{N}_0^+$ and are therefore arranged in a "ladder-like" sequence does not follow necessarily. In contrast to other authors (such as R. Feynman [11]), I assumed $i \in \mathbb{N}_0^+$ in earlier work [16,18]; for the sake of completeness, however, this assumption will not be imposed here, so as to allow for the remaining possibility.

The third, green curve results from that model of L. Boltzmann from which the Boltzmann factor (and the relation between entropy and statistics) is derived [2]. His fundamental assumption is that a molecule can absorb an arbitrary number of quanta of the energy ε. From his model, as from that of Einstein, it follows that $n_{i+1}/n_i = r/(1+r)$ (red curve), but as an approximation for large r (many quanta per molecule) he infers $n_{i+1}/n_i = \exp(-1/r)$ (green curve). For L. Boltzmann, the quanta are not real (but merely a mathematical device); he may therefore conceive them as arbitrarily small and arbitrarily numerous. However, they are real, and many of them are by no means particularly frequent (relative to the number of molecules). The difficulties arise when an approximation is employed in a regime (significantly fewer quanta than molecules) in which it is not applicable, yet nevertheless reproduces the empirical findings correctly—unlike the exact equation.

Figure 1 shows that, for example, for $r = 0.1$ (on average one quantum per ten molecules), the ratio n_1/n_0 for the two-state system, or n_{i+1}/n_i for the monochromatic resonator, is likewise close to 0.1, as one would expect if the number of quanta per molecule determines the molecule's energy state.

For the approximation that yields empirically consistent results (green curve), however, this is not the case.

In order to resolve this contradiction, one might postulate that the energy quanta exchanged are far smaller (and hence more frequent) than is presently assumed. Alternatively, one might suppose that the resonators are much larger, i.e. that they do not correspond to individual molecules but to ensembles. In both cases, the approximation $n_{i+1}/n_i = \exp(-1/r)$ would be justified. One might even conjecture that the energy distribution among molecules does not arise from a stochastic process at all.

Alternatively, one may assume that one of the assumptions underlying the models of M. Planck and A. Einstein is fundamentally incorrect. This is the hypothesis to be examined here.

Einstein's Model of the Interaction of Light with Matter

A. Einstein considers "*a gas consisting of identical molecules … which are in statistical equilibrium with thermal radiation. Each molecule shall be capable only of a discrete series of states …*". As stated above, we shall assume here that these states may be separated by arbitrary energy intervals (generally not arranged in ladder-like form) and that A. Einstein therefore had in mind not a monochromatic resonator but rather—perhaps under the influence of Niels Bohr's 1913 theory of atomic spectra [1], which he mentions in his paper—a hierarchical orbital model.

From the Boltzmann factor, or from thermodynamic considerations which he does not elaborate in detail, he infers that the relative number of molecules n_i occupying state Z_i (Figure 2) is given by (notation modified; the following equation corresponds to his Eq. 2):

$$n_i = \mathrm{e}^{-\frac{E_i}{kT}} \quad (3)$$

In contrast to the original (his Eq. 2), the "statistical weight of Z_i", a temperature-independent constant that plays no further role later on, is omitted here. E_i denotes the energy level of Z_i. From this he deduces ($i, j = 0, \ldots, s$):

$$n_j / n_i = \mathrm{e}^{\frac{E_i - E_j}{kT}} \quad (4)$$

The molecular energy states Z_i, Z_j, etc., are mutually exclusive states, and naturally each molecule must occupy one of them; thus one must have:

$$n_0 + \ldots + n_i + n_j + \ldots + n_s = 1 \quad (5)$$

For small s, this additional condition becomes problematic. This is particularly evident if one considers a hypothetical molecule possessing only two energy states Z_0 and Z_1 ($s = 1$). In that case, instead of Eq. 5 we have $n_1 = 1 - n_0$ (see also Figure 1, blue curve), and for the ratio of the populations of the two states, $n_1/n_0 = (1 - n_0)/n_0$, Eq. 4 (also Eq. 4 in Einstein's paper) does not hold. If, on the other hand, $n_i + n_j << 1$ because there exist very many possible states, one may assume that Eq. 3, and therefore also Eq. 4, can be valid.

However, does the energy distribution given by Eq. 4 also follow from the kinetics of Einstein's model? The great advantage of the monochromatic resonator in the models of L. Boltzmann [2] and M. Planck [13,14] lies in the ladder-like arrangement of the energy states ($i \epsilon \mathbb{N}_0^+$), which yields a series that is straightforward to handle [16]. If the energy states are separated by arbitrary intervals and are mutually exclusive, this procedure cannot be applied; under these circumstances, the resulting energy distribution cannot be inferred from the energy-exchange processes postulated by A. Einstein, nor can it be derived from the kinetics of the model, as will become evident in what follows (if one considers only two states Z_i and Z_j, this does not imply that the arguments applicable to a two-state system may be adopted whenever $n_i + n_j < 1$). Eq. 4 does not represent the only possible energy distribution compatible with the model.

In addition to spontaneous emission, A. Einstein postulated in his model a further form of emission induced by the field, that is, by photons (Figure 2). The reason for this postulate lay in the classical description of the interaction between resonator and field. A. Einstein writes: "*In the case of the resonator … the incident radiation … may just as well produce a decrease as an increase of energy*." If a resonator can both absorb energy from the field and emit energy into it, the same must be possible in quantum theory. Accordingly, a light quantum may either be absorbed or trigger the emission of a further photon of the same energy ε.

A. Einstein assigns three kinetic constants to the three different forms of interaction between light and matter. In the notation used here, let α denote the constant for absorption, β for induced emission, and γ for spontaneous emission. Let Z_j be the energetically higher state relative to Z_i (Figure 2). In addition to $\mathbf{n}_i$, we also require the relative frequency of photons m, where $m = M/N$, and M is the number of photons in the same volume to which the number of molecules N refers (A. Einstein used the radiation intensity $\rho = mh\nu$ instead of photon number in his calculations).

The transition from Z_j to Z_i occurs via induced and spontaneous emission (Figure 2). The former must be proportional not only to the population of molecules in the higher-energy state but also to the photon frequency:

$$Z_j \rightarrow Z_i: \quad \beta\, m n_j + \gamma\, n_j = n_j\,(\beta\, m + \gamma)$$

The transition from Z_i to Z_j occurs via absorption. Here both the photon frequency and the population of molecules in the lower-energy state are relevant:

$$Z_i \rightarrow Z_j: \quad \alpha\, m n_i$$

It follows (t: time):

$$\Delta m/\Delta t = \beta\, m n_j + \gamma\, n_j - \alpha\, m n_i$$

In thermal equilibrium, $\Delta m/\Delta t = 0$, which yields:

$$m\,(\alpha\, n_i - \beta\, n_j) = \gamma\, n_j$$

A. Einstein now concludes that the kinetic constants for absorption and induced emission must be equal: $\alpha = \beta$. This is not without justification. Within classical physics, in the interaction between resonator and electromagnetic field, the former may either absorb energy from the field or emit energy into it. Which process occurs depends on the phase difference between field- and resonator-oscillation. In the case of a non-coherent field, both processes should occur with equal probability once a contact between a photon and a molecule has taken place. Thus:

$$\alpha\, m\,(n_i - n_j) = \gamma\, n_j$$

Using Eq. 4, one may substitute for n_j and finally obtain—if one assumes that the photon energy ε corresponds to the energy difference between the two levels, i.e. $\varepsilon = E_j - E_i$:

$$m = \frac{\gamma}{\alpha}\,\frac{1}{e^{\frac{\varepsilon}{kT}} - 1} \qquad (6)$$

With an appropriate choice of γ/α and by setting $\varepsilon = h\nu$, this corresponds to M. Planck's relation between ρ and T, i.e. Eq. 1.

Equation (6) may now be rearranged, again using $\alpha = \beta$, to yield:

$$e^{-\frac{h\nu}{kT}} = \frac{\beta m}{\beta m + \gamma} \qquad (7)$$

The right-hand side of Eq. 7 corresponds to the ratio of the number of induced emissions to the total number of emissions, which evidently depends on ν and T. This has consequences for the coherence of the field, since induced emission ($\beta\ m$) produces coherent photon pairs—as demonstrated by the laser—whereas spontaneous emission (γ) produces photons of random phase (as well as propagation direction and polarisation). With increasing temperature T and decreasing photon frequency ν, coherence should increase, and according to Einstein's model a certain degree of coherence is always present. This is problematic, however, because the identification $\alpha = \beta$ was justified by assuming that the field is non-coherent. Moreover, this result of Einstein's model has no counterpart in classical physics.

Furthermore, it follows that $n_j/n_i = \beta\, m/(\beta\, m+\gamma)$. This is all that can be learned from the model about the ratio of the molecular energy states (provided one does not assume from the outset that $n_j/n_i = exp(-h\nu/(kT)$ and provided one assumes that the model molecules are not monochromatic resonators).

Summarised

- From the kinetics of Einstein's model, one cannot deduce the distribution of energy among the molecules (unless one assumes that his model is based on monochromatic resonators). It does not follow necessarily that the energy distribution is described by Eq. 4 (the Boltzmann factor). In the model, the energy states or levels are mutually exclusive, i.e. each molecule represents one such state.
- According to Einstein's model, the electromagnetic field is always coherent to some extent, which is incompatible with the assumption $\alpha = \beta$; yet without this assumption the radiation law (Eq. 1) cannot be derived from the model.
- The model cannot readily be generalised to allow for arbitrary degrees of field coherence.

An Alternative Derivation of Planck's Radiation Law Based on the "Pairwise Interference Model of QM" (PIMOQ)

The blackbody is an idealised state of matter that completely absorbs all incident electromagnetic radiation and emits characteristic thermal radiation. It is, for example, closely approximated by stars or glowing coals. It emits and absorbs a continuous spectrum of radiation, which is not the case for isolated atoms or molecules. The highly complex visual pigments of our retina display a continuous absorption spectrum; however, this does not coincide with that of a blackbody. Gases, which consist of more or less free molecules, likewise do not in general exhibit the properties of a blackbody.

What, then, is distinctive about a blackbody? In the author's view, its defining feature is that quanta of different colour, or energy, can recombine freely within it; that is, they may be described as mutually independent. There is no restriction between them of the kind whereby a quantum of energy ε_i can be absorbed by a molecule only after a quantum of energy ε_j has been absorbed, or vice versa. In other words, there are no hierarchical orbitals. From a theoretical standpoint, this entails a modification of perspective: rather than considering the energy states of a black-body molecule, it is more appropriate to conceive of it as a reservoir of quanta (the indices i,j therefore refer in the following not to molecular energy states but to the energies of the quanta).

A further property of the blackbody, in my view, is that within it—by analogy with Eq. 4—the following relation holds (r_i, as before, denotes the frequency of quanta of colour ε_i relative to the number of molecules N):

$$r_i = \mathrm{e}^{-\frac{\varepsilon_i}{kT}} \qquad (8)$$

This is not merely a consequence of the exchange of quanta between molecules (as already shown [16,18], plausible models yield incorrect results in certain regimes), but equally of the distribution of energy within a given molecule. I regard Eq. 8 as a fundamental property of the blackbody, which I shall not attempt to explain further here. The following, however, holds: owing to free recombinability, for three quanta of the energy levels ε_i, ε_j and ε_l, if $\varepsilon_l = \varepsilon_i + \varepsilon_j$, then it must also be the case that $r_l = r_i\, r_j$, or, according to Eq. 8:

$$r_l = \mathrm{e}^{-\frac{\varepsilon_i}{kT}}\mathrm{e}^{-\frac{\varepsilon_j}{kT}} = \mathrm{e}^{-\frac{\varepsilon_i+\varepsilon_j}{kT}} = \mathrm{e}^{-\frac{\varepsilon_l}{kT}} \qquad (9)$$

doi:10.20944/preprints202603.0962.v1

thus demonstrating that the relation expressed in Eq. 8 is likewise satisfied for r_l. The additivity of energy on the one hand, and the requirement of free recombinability on the other, therefore enforce an exponential relationship, provided one assumes a strict correspondence between the energy of the quanta and their frequency. The quantity kT/ε_i represents the ratio of the mean energy per molecule (averaged over the entire spectrum of the radiation) to the energy of the particular quantum under consideration.

Different quantum energies do not constitute mutually exclusive states within a molecule, in contrast to the state of the molecule as a whole (a molecule may store several quanta simultaneously, though not more than one of a given colour). Consequently, no difficulty arises with Eq. 8 if we note that, when r_i molecules possess a quantum of colour ε_i, a fraction $1-r_i$ of the molecules does not possess this property (this effectively replaces Eq. 5). We accept that each molecule can "store" only one quantum of a given colour, but many of different ones, which do not influence one another (Figure 3).

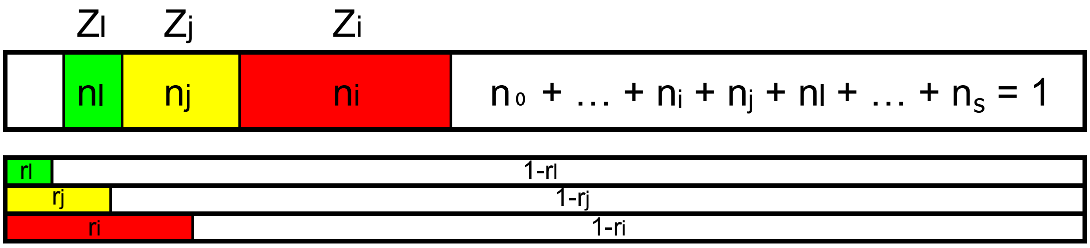

Figure 3. A comparison is made between the exclusivity of molecular energy states in A. Einstein's model (top) and the unrestricted recombinability of quanta of differing energies in the alternative model (bottom). A row symbolizes the entirety of the molecules.

The information presented suffices to attempt a very simple derivation of Eq. 1. We consider only a single colour and therefore omit the index. We assume two processes:

- A photon of energy ε is emitted with a probability proportional to the relative number of molecules containing a quantum of this colour: γr.
- A photon of energy ε is absorbed with a probability proportional to the photon frequency and to the relative number of molecules that do not contain a quantum of this colour (a molecule can absorb a photon of a given colour only if it has not already absorbed one of that colour): $\alpha\delta\, m(1-r)$.

In addition to the kinetic constant α, I have introduced a second constant δ, intended to represent the probability that a photon and a molecule encounter one another. The constant α then denotes the probability that, in such a case, an interaction actually occurs (this separation could, of course, equally have been introduced in the model of A. Einstein).

$$\Delta m/\Delta t = \gamma r - \alpha\delta\, m(1-r) \qquad (10)$$

In equilibrium, $\Delta m/\Delta t = 0$. It follows that:

$$m = \frac{\gamma}{\alpha\delta}\frac{r}{1-r} = \frac{\gamma}{\alpha\delta}\frac{1}{\frac{1}{r}-1}$$

and, upon application of Eq. 8:

$$m = \frac{\gamma}{\alpha\delta}\frac{1}{e^{\frac{\varepsilon}{kT}}-1} \qquad (11)$$

Formally, Eqs. 6 and 11 are essentially consistent; differences arise, however, in their interpretation. In the alternative derivation no mention has thus far been made of stimulated emission, nor was there any necessity to set $\alpha = \beta$, since β did not appear. The reason for this is not that such processes do not exist; the laser demonstrates that they do. However, we assume that in a non-coherent field no stimulated emissions occur (apart from statistical fluctuations), which is in fact the only way to maintain this state of the field, since stimulated emission "produces" pairwise coherent photons. Moreover, in the alternative model stimulated emission and absorption are evidently not complementary events.

With regard to field coherence, black-body radiation represents one extreme; in the author's view, the interference experiment represents the other [15], since in the latter—according to the interpretation of the PIMOQ—practically only stimulated emissions play a role (such experiments furthermore permit manipulation of the coherence of the local field). The difference between the PIMOQ and quantum theory in the Copenhagen interpretation shall be outlined only briefly here. To present the Copenhagen interpretation, P. Dirac (1947) [5] may be quoted:

"*Each photon … interferes only with itself. Interference between two different photons never occurs*."

In the PIMOQ, by contrast, it is always pairs of photons that interfere, never a photon with itself. Interference requires the mediation of matter. The superposition of possible states that are supposed to collapse upon measurement likewise does not occur in the PIMOQ. P. Dirac further writes:

"*Some time before the discovery of quantum mechanics people realized that the connexion between light waves and photons must be of a statistical character. What they did not clearly realize, however, was that the wave function gives information about the probability of one photon being in a particular place and not the probable number of photons in that place*."

In agreement with A. Einstein (1936) [10], the PIMOQ maintains that quantum theory permits only statistical statements and none that refer to an individual photon.

According to the Copenhagen interpretation, it is meaningful only to formulate hypotheses concerning the results of experiments, but not to devise intuitive conceptions of the underlying processes:

"*Only questions about the results of experiments have a real significance and it is only such questions that theoretical physics has to consider*."

Within the PIMOQ, it is permissible to raise background questions concerning the nature of an interaction (although the mathematically correct result must, of course, ultimately be obtained). With regard to stimulated emission, this has already been undertaken [15] and is summarised here.

In order to identify, for stimulated emission in quantum theory, a counterpart to the phase difference between field and resonator in classical physics, we may, following De Raedt *et al.* (2005) [4], assume that the absorbed photon transfers to the molecule not only its energy but also its phase message φ (which may be visualised as the position of a pointer on a clock face), and thus the information concerning its travel time modulo $1/\nu$. This information remains unchanged for as long as the photon is stored.

Upon collision of the molecule with a second photon, its message is compared with the stored one. Depending on the magnitude of the phase difference $\xi_{ij} = \varphi_i - \varphi_j$ $(\mathbf{i,j = 1, \ldots, M})$, stimulated emission occurs with probability p_{ij}, the result being the release of a photon pair with (nearly) identical properties (frequency, phase, polarisation, trajectory). The attributes of the "later" photon are those that are adopted. We assume that p_{ij} should increase with increasing similarity of the phases. Furthermore, the range of the cosine (−1 to 1) must be taken into account. We therefore choose for p_{ij}:

$$p_{ij} = \frac{1 + cos\xi_{ij}}{2} \qquad (12)$$

The frequency β with which stimulated emissions occur now corresponds to the difference between emission events and those that "cancel" the emissions again, the latter occurring with probability $q_{ij} = 1 - p_{ij}$ (in this model β is, of course, not a constant).

$$\beta = \sum_{i,j} m_i m_j \left(p_{ij} - q_{ij}\right) \qquad (13)$$

In a non-coherent field, $p_{ij} = q_{ij} = 0.5$ and hence $\beta = 0$. In a perfectly coherent field, $\beta = 1$. Using Eq. 12, one obtains:

$$\beta = \sum_{i,j} m_i m_j cos\xi_{ij} \qquad (14)$$

As I have shown elsewhere [15], this equation yields the same result as the amplitude-squared representation in quantum theory for the probability of an event—here, stimulated emission—when the Born rule is applied.

$$|A|^2 = \sum_i m_i e^{\varphi_i \sqrt{-1}} \sum_i m_i e^{-\varphi_i \sqrt{-1}}$$

The mathematical agreement with quantum theory is therefore established. The interpretation, however, is difficult. In an earlier publication [15], I adopted on the one hand the position that the complementary event to stimulated emission is absorption (as was also done by A. Einstein), and on the other hand that Eq. 13 presupposes a monochromatic resonator and cannot be "reasonably" interpreted in a two-state system (since in that case superposition must be assumed). As we have here dispensed with the monochromatic resonator and do not regard absorption as a complementary event, only a pragmatic viewpoint remains: namely, that there exists no complementary event to stimulated emission at all. The counter-probabilities q_{ij} may formally be eliminated by replacing Eq. 13, as an intermediate step towards the more relevant Eq. 14, with
$\beta = \Sigma\, m_i m_j\, (2p_{ij}-1)$. In any case, Eq. 14 states that the coherence of the field determines the number of induced emissions and thus the extent, or the directionality, of the energy exchange between the field and matter.

The PIMOQ is not a classical theory, since it assumes that a photon can carry information about its travel time, although according to relativity no time elapses for a particle moving at the speed of light. For δ, one obtains from Eq. 1 and Eq. 11:

$$\delta = c^3/8\pi\nu^2 \qquad (15)$$

provided that we assume $\gamma/\alpha = 1$. In the PIMOQ, photons follow classical trajectories and there are no possible paths that superpose. A more detailed discussion of this topic can be found in Ref. 18.

Within the framework of PIMOC, two scenarios in which stimulated emission is significant shall be briefly discussed, namely the interference experiment and the laser.

In an interference experiment such as the double-slit experiment, the local coherence of the field at the detector or observation screen is determined by the light source and the experimental arrangement [15]. Locally, it varies in the horizontal direction (i.e. perpendicular to the slits) from $\beta = 0$ to $\beta = 1$ (β is given by Eq. 14 or may be replaced by $|A|^2$ and describes the field coherence). At room temperature, practically all molecules of the detector would be in the lower-energy state; however, due to the irradiation the opposite is the case, and the vast majority of molecules contain quanta of the energy of the light reaching them from the source. Consequently, r is only slightly smaller than one and $1-r$ is approximately zero (r is given by Eq. 8 only in thermal equilibrium with a non-coherent field). Although absorption is certainly important for the process, it does not play a role in the balance (see Eq. 10). In principle, this yields:

$$\Delta m/\Delta t \approx \gamma + \beta\delta\, m \qquad (16)$$

However, owing to the conditions and constraints of the system, this leads not to an exponential but only to a logistic increase in m. Because β varies periodically along the horizontal direction of the screen, the interference fringe pattern arises. It may be surprising that even at locations of destructive interference absorption is insignificant in the balance; however, here as well almost all molecules are at a higher energy level, but because of the phase difference of π between the partial beams no stimulated emissions occur. Since the coherence of the field is determined by the light source and the experimental arrangement (the double slit)—so to speak from outside—it is not altered by the stimulated emissions. Consequently, no feedback occurs.

In the case of the laser, Eq. 16 also applies with the aforementioned restriction. That r is only slightly smaller than one is achieved in this case, for example, by pumping, that is, by the continuous supply of quanta bound in matter. In order for a steady-state flow equilibrium to arise ($m+r=z$, where z is a constant), a fraction of the photons must be removed from the system. Mirrors ensure that the other light quanta stay in the system for a relatively long time, so that feedback occurs: the field coherence ($\beta > 0$) gives rise to stimulated emissions, which in turn increase the field coherence. Ultimately, this leads to positive density-dependent selection, as I have described elsewhere [17].

In summary, the following emerges:

- From the knowledge of the mean molecular energy kT of the blackbody, one can determine the relative proportion of quantum-absorbing ($1-r$) and quantum-emitting (r) molecules for each quantum colour ε, provided that the field is non-coherent.
- $|A|^2$ or, equivalently, β describes the degree of field coherence.
- The field coherence determines the directionality of the energy exchange between matter and field (induced emissions).
- This directionality, in turn, reinforces the field coherence.

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