Chapter 13
A Mechanistic Reading of Quantum Laser Theory

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13.1 Introduction

I want to show that the quantum theory of laser radiation provides a good example of a mechanistic explanation in a quantum physical setting. Although the physical concepts and analytical strategies I will outline in the following do admittedly go somewhat beyond high school knowledge, I think it worth going some way into the state-of-the-art treatment of the laser, rather than remaining at a superficial pictorial level. In the course of the ensuing exposition of laser theory, I want to show that the basic equations and the methods for solving them can, despite their initially inaccessible appearance, be closely matched to mechanistic ideas at every stage.

In the quantum theory of laser radiation, we have a decomposition into components with clearly defined properties that interact in specific ways. This dynamically produces an organization that gives rise to the macroscopic behavior we want to explain. I want to argue that a mechanistic reading is not one that can be overlaid on laser theory so that it coheres with the mechanistic program, but rather that the quantum theory of the laser is inherently mechanistic, provided that the notion of a mechanism is slightly broadened. As I will show, the pieces required to identify the workings of a mechanism can be seen directly on the level of the basic equations. And this applies even more clearly to the following derivation than to the more picturesque semiclassical derivations, because it starts on the most basic level of quantum field theory, where *all* the relevant parts of the laser mechanism are described in detail, e.g., atoms with internal structure and specific behavior in isolation and interaction.

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B. Falkenburg and M. Morrison (eds.), *Why More Is Different*,
The Frontiers Collection, DOI 10.1007/978-3-662-43911-1_13

When all is said and done, the quantum theory of laser radiation is a neat example of a *mechanistic* explanation because we have an explanation that shows how the stable behavior of a compound system reliably arises purely on the basis of interactions between its constituents, without any coordinating external force.[1] The proof that quantum laser theory can be understood as supplying mechanistic explanations has a number of important implications. Most importantly, it shows that mechanistic explanations are not limited to the classical realm. Even in a genuinely quantum context, mechanistic reasoning can survive.[2] Mechanistic explanations are attractive because they often provide the best route to effective interventions. Moreover, understanding the general mechanisms involved in self-organizing systems such as the laser allows one to transfer certain results to other less well understood systems where similar mechanisms (may) operate.

13.2 What Is a Mechanism?

According to the mechanical philosophy of the seventeenth century, one could explain everything by the mechanical interaction (push and pull) of tiny building blocks. In contrast, today's mechanists, also called the "new mechanists", have a more modest point. They do not claim that everything can and must be explained in terms of mechanisms. For instance, electromagnetic interactions may well not be mechanistically explicable. The crucial point for the new mechanists is that mechanistic explanations play the dominant role in most sciences, something not appropriately represented in the standard philosophy of science. In many cases, biology, but also physics, and in particular in its applied branches, do not focus primarily on laws. They still play a role, but not a prominent one. Accordingly, the philosophy of science should be amended as far as mechanisms are concerned.

Whereas the *interaction theory of mechanisms* (Glennan 2002) says that a "mechanism for a behavior is a complex system [in the sense of compound system, MK] that produces that behavior by the interaction of a number of parts, where the interactions between parts can be characterized by direct, invariant, change-relating generalisations" (p. S344), the *dualistic approach* (Machamer et al. 2000) has it that "[m]echanisms are entities and activities organised such that they are productive of regular changes from start or set-up to finish or termination conditions" (p. 3). Today there are a number of proposals for a consensus formulation. Illari and Williamson (2012) propose the following unifying characterization of mechanisms: "A mechanism for a phenomenon consists of entities and activities organized in such a way that they are responsible for the phenomenon" (p. 120). Thus Illari and Williamson see the identification of three elements as essential for a mechanism, namely (i) responsibility for the phenomenon, (ii) "entities and activities", and (iii)

[1] This fact is also the reason why the laser is a paradigmatic example of a self-organizing system.

[2] See Kuhlmann and Glennan (2014) for a more comprehensive discussion of why quantum mechanics seems to undermine mechanistic explanations, and why in fact it doesn't.

organization. Bechtel and Abrahamsen (2011) see as the "key elements of a basic mechanistic explanation […] (1) the identification of the working parts of the mechanism, (2) the determination of the operations they perform, and (3) an account of how the parts and operations are organized so that, under specific contextual conditions, the mechanism realizes the phenomenon of interest" (p. 258). I will take this proposal as the background for the following analysis, in which I will check whether and how these requirements are fulfilled.

13.3 Quantum Laser Theory Read Mechanistically

13.3.1 The Explanandum

In his famous paper on black body radiation Einstein (1917) introduced the idea of 'induced' or 'stimulated' emission of light quanta, later called photons. This idea already suggests the possibility of amplifying light of a chosen wavelength in a systematic way, and this is what was realized technically by the laser (light amplification by stimulated emission of radiation) in 1960. Lasers are light sources with outstanding properties, such as very high monochromaticity (temporal coherence), a high degree of collimation (spatial coherence), and high intensity of radiation. For weak energy supply, lasers radiate conventional lamp light, e.g., a superposition of numerous wavelengths. Once the energy supply exceeds the so-called laser threshold, all the atoms or molecules inside a laser begin to oscillate in a single common mode, emitting light of (ideally) just one wavelength and therefore one color (Fig. 13.1).

The aim of laser theory is to explain how the interaction of the photon-emitting atoms produces laser light. That is, the goal is to calculate the dynamics of the compound system, i.e., the laser, in terms of its interacting subunits. The dynamics is described by differential equations, i.e., by equations that contain a function together with its derivative(s). Differential equations constitute a core part of every physical theory. With a differential equation which relates a state function to its temporal derivatives, knowing the state at one time allows one to determine the state at all later times. For a complex system, such as a laser, the basic differential equations can be horrendously complicated because of their sheer number and mutual coupling. For example, if the number of laser-active atoms is of the order of 10^{14}, one gets 10^{18} differential equations. Thus, apart from determining the relevant set of differential equations, the ambition of laser theory is to solve this system of differential equations, which is a formidable task.

13.3.2 Specifying the Internal Dynamics

In the semiclassical laser theory, only the atoms are described by quantum theory, whereas the electrical field in the laser cavity is assumed to be classical. This is a

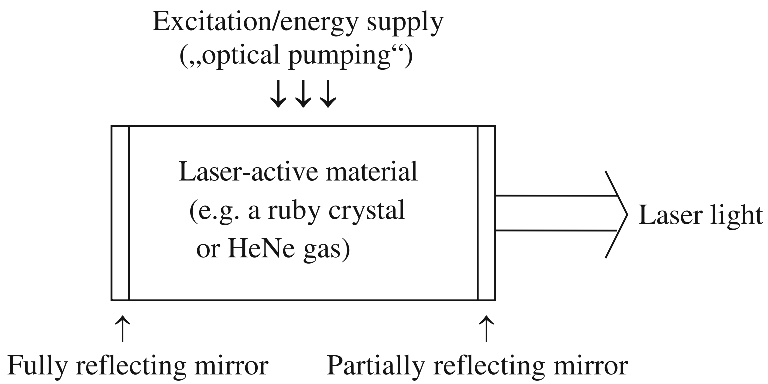

Fig. 13.1 Schematic design of a laser

comparatively simple but already very powerful approach. However, in the present context, I start with the more advanced quantum theory of laser radiation for an obvious reason: we should avoid assuming any classical physics when we want to show that classical mechanistic concepts are applicable even in the quantum realm. Moreover, from an ontological point of view, the quantum theory of laser radiation has yet another advantage: the basic equations for the dynamics of laser radiation can be derived from first principles, i.e., by starting with fundamental equations. In the following I will introduce these basic dynamical equations in some detail, because they are crucial for demonstrating the mechanistic nature of laser theory.

The first important set of equations for laser radiation are the **field equations**, which specify the time dependence of the electromagnetic field operators b_λ. In the classical case, the b_λ are the amplitudes of possible states of oscillation of the electromagnetic field inside the laser cavity or 'resonator', counted by the index λ (the wavelength). This means that each individual $b_\lambda(t)$ specifies how much the λ-th mode is excited. In a quantum setting, b_λ^+ (the complex conjugate of b_λ) and b_λ become creation and annihilation operators for the laser field, i.e., each occurrence of b_λ^+, or b_λ, in a formula (e.g., a Hamiltonian, see below) represents the creation, or annihilation, of a photon with quantum number λ (classically the wavelength).

The basic equations in laser theory capture the dynamics of the essential quantities. In the quantum setting used in laser theory, the time dependence of an operator A is determined by the Heisenberg equation of motion[3]

[3] I work in the so-called 'Heisenberg picture'. As is well-known quantum mechanics can be formulated in different mathematically and physically equivalent ways. The two best-known representations or 'pictures' are the Schrödinger picture and the Heisenberg picture. Quantum mechanics is mostly formulated in the Schrödinger picture, where the state is time-dependent while the observables for position and momentum are time-independent. In the Heisenberg picture, on the other hand, observables carry the time-dependence, whereas the states are time-independent. Mathematically, the Heisenberg picture is related to the Schrödinger picture by a mere basis change, and thus physically both pictures lead to the same measurable quantities, of course. In

$$\frac{d}{dt}A \equiv \dot{A} = \frac{i}{\hbar}[H, A] \equiv \frac{i}{\hbar}(HA - AH), \tag{13.1}$$

where H denotes the Hamilton operator, or 'Hamiltonian' for short, which represents the total energy of the system.[4] So the first step in the quantum theory of laser radiation—as in most other quantum physical treatments of the dynamics of a given system—consists in finding the Hamiltonian of the system. In our case, the Hamiltonian of the whole system, i.e., the laser, can be decomposed as follows

$$H = H_f + H_A + H_{Af} + H_{B_1} + H_{B_1-f} + H_{B_2} + H_{B_2-A} \tag{13.2}$$

where H_f denotes the Hamiltonian of the light field, H_A that of the atoms, and H_{Af} that of the interaction between the atoms and the field; H_{Bi} is the Hamiltonian of heat bath i and $H_{Bi\text{-}f}$ of the interaction between heat bath i and the field. Even on this very first level, mechanistic ideas can already be clearly identified, since the total Hamiltonian is neatly split up into parts that comprise the behavior of the system's components in isolation, followed by all the interactions between these components and with any other relevant systems. A more detailed description of all these Hamiltonians will be given now.

H_f is the Hamiltonian for the electromagnetic light field, and H_A the Hamiltonian for the *atoms* inside the laser, which in turn sums over the Hamiltonians of all the individual atoms, i.e., each atom has its own Hamiltonian—notwithstanding the indistinguishability of "identical" quantum particles.[5] These two parts of the total Hamiltonian determine the behavior of the light field and of the laser atoms in isolation, i.e., if there is no interaction whatsoever between the field and the atoms or with any other entities, such as the environment of the system. The next part of the total Hamiltonian, H_{Af}, captures the way the atoms interact with the field modes. One term that appears in this Hamiltonian for the interaction between the field modes and the atoms is $a^+_{1,\mu} a_{2,\mu} b^+_\lambda$, which represents (read the formula from right to left) the creation of a photon in field mode λ, the annihilation of an electron in state 2 (the higher energy level), and the creation of an electron in state 1 (the lower energy level), a sequence which can be grasped quite intuitively (see Fig. 13.2).

So far we have three essential parts of the total Hamiltonian, which seems to be all we need to know in order to determine the dynamics that leads to laser light. And in fact, the semiclassical laser theory gets pretty far without considering

(Footnote 3 continued)
some respects, the Heisenberg picture is more natural than the Schrödinger picture (in particular, for relativistic theories) since it is somewhat odd to treat the position operator, for instance, as time-independent. Moreover, the Heisenberg picture is formally closer to classical mechanics than the Schrödinger picture. For this reason it is advantageous to use the Heisenberg picture if one intends to compare the quantum and the classical case, which I want to do for the laser.

4 Note that the first and the last part of the above row of equations are just definitions, indicated by "≡".

5 See Haken (1985), p. 236ff.

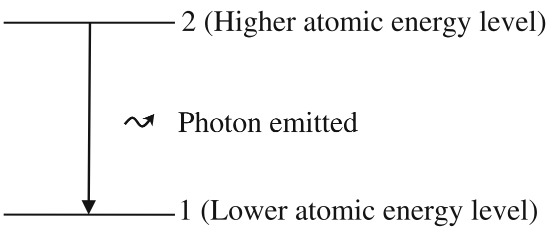

Fig. 13.2 Schematic representation of a field-atom interaction

anything other than the field (described classically), the atoms, and their interaction. However, it turns out that the semiclassical laser theory is unable to explain the transition from conventional lamp light to laser light, which occurs at the 'laser threshold', and some details of the coherence properties of laser light. What has been left out so far is damping. The light field inside the laser is damped due to the transmissivity of the mirrors and other cavity losses, and the atoms are also damped by various processes (more below). Damping of a quantity always produces fluctuations, which in turn have important consequences. In the Hamiltonian, damping is accounted for in terms of an additional interaction (or coupling) of the light field with a 'heat bath', called B_1, which is taken to cover all the above-mentioned processes, as well as a further interaction of the atoms with a second heat bath, B_2, each of which has its own Hamiltonian.[6]

Let us take stock. In order to understand what happens in a laser we need to know how the basic physical quantities, in quantum theory represented by operators, evolve in time. Due to the Heisenberg equation of motion (1), we need the total Hamiltonian of the laser in order to determine the time evolution of any operator in which we are interested. Thus the Hamiltonian characterizes those specifics of our system that determine how it evolves in time, in particular when its parts interact with each other. As we have seen the basic dynamical setting of the quantum theory of laser radiation—given by the total Hamiltonian of the laser system—rests on a clear separation of different relevant components, whose behavior is described both in isolation and in mutual interaction. This observation will play a crucial role in our philosophical assessment concerning the mechanistic nature of the quantum theory of laser radiation.

Now let us begin to actually write down the equations of motion for the relevant physical quantities. In other words, we want to formulate those equations that tell us the dynamics of the important quantities, i.e., how they evolve in time. The first set of such equations determines the dynamics of the laser's light field in terms of its electromagnetic field operators b (we already described the significance of b, just before we introduced the Hamiltonian that determines its dynamics). In order to get

[6] The fluctuations comprise thermal and quantum fluctuations, giving rise to additional statistical correlations between the atoms and the field. Bakasov and Denardo (1992) show in some detail that there are some corrections due to the "internal quantum nature" of laser light, which they call "internal quantum fluctuations".

those equations, we need to insert the relevant parts of the total Hamiltonian into the Heisenberg equation of motion (1), which gives us the following set of differential equations for the quantized *field* modes:

$$\dot{b}_\lambda = -i\omega_\lambda b_\lambda + \kappa_\lambda b_\lambda - i\sum_\mu g^*_{\mu\lambda}\alpha_\mu + F_\lambda(t) \tag{13.3}$$

The first term refers to the freely oscillating field and the second to the damping of the field mode due to the interaction between the field and the heat bath in the laser cavity. The third term accounts for the interaction between the field and the atoms, and the fourth is an operator that describes a fluctuating force. The index μ counts the atoms that are excited inside the laser and produce the light field. ω_λ is the frequency of the λ-th mode, the coupling constant $g_{\mu\lambda}$ specifies the interaction between the μ-th atom and the λ-th mode, and α_μ is the operator for the polarization of the μ-th two-level atom.[7] Classically, the (formally identical) terms -$ig^*_{\mu\lambda}a_\mu$ reflect the way the mode amplitudes (i.e., the b_λ) change due to the oscillating atomic dipole moments. Mathematically, these terms lead to a coupling with the next set of differential equations for the dynamics of the atomic variables α_μ (more below). The $\alpha_\mu \equiv a^+_{1,\mu}a_{2,\mu}$ represent the annihilation of an electron in state 2 (the higher energy level), while an electron in state 1 (the lower energy level) is created. The above-mentioned damping of the light field inside the laser is captured by the damping constant (or 'relaxation speed') κ_λ. Since damping of a quantity produces fluctuations in its turn, one introduces the stochastic force $F_\lambda(t)$, which accounts for fluctuations due to any kind of dissipation (loss of directed energy, e.g., by friction or turbulence).

The next sets of differential equations, the **matter equations**, determine the dynamics of the laser-active atoms inside the laser cavity. The first group of equations

$$\dot{\alpha}_\mu = -(iv + \gamma)\alpha_\mu + i\sum_\lambda g_{\mu\lambda}d_\mu b_\lambda + \Gamma_\mu(t) \tag{13.4}$$

with Hermitian conjugate

$$\dot{\alpha}^+_\mu = (iv - \gamma)\alpha^+_\mu - i\sum_\lambda g_{\mu\lambda}d_\mu b^+_\lambda + \Gamma_{\mu+}(t) \tag{13.5}$$

[7] One can make a few simplifications (single laser mode, coupling constant independent of λ and μ) which ease the ensuing calculations. However, in the present context they are not helpful for a better understanding because they require further explanation and justification and widen the gap with realistic situations. For this reason I use the equations on p. 246 in Haken (1985), but without the simplifications introduced on p. 123, and that means with additional indices, which are still there on pp. 121ff.

specify how the atomic polarization changes in time. These equations are again coupled with those for the field operators b_λ above, since the field has an effect on the dynamics of the atoms. Still another coupling stems from the occurrence of the variable d_μ, which describes the **atomic inversion** $d_\mu \equiv (N_2 - N_1)_\mu$, i.e. the difference in occupation number of the energy levels (which are taken to be two for simplicity) that the laser-active atoms can be in. In the end, the temporal change in the atomic inversion is given by the differential equations

$$\dot{d}_\mu = \gamma_{\|}(d_0 - d_\mu) + 2i \sum_\lambda \left(g^*_{\mu\lambda} \alpha_\mu b^+_\lambda - g_{\mu\lambda} \alpha^+_\mu b_\lambda \right) + \Gamma_{d,\mu}(t), \tag{13.6}$$

which is the second group of **matter equations**. $\Gamma_\mu(t)$ and $\Gamma_{d,\mu}(t)$ account for those fluctuations that are connected with the damping constants γ and $\gamma_{\|}$.

The damping constants in the four laser equations above refer to different kinds of damping processes, and this is in fact crucial for the solution of the full system of coupled non-linear differential equations for laser light. Classically, the damping constant (or 'relaxation speed') κ_λ captures the damping of the field amplitude b_λ in the resonator if there is no interaction between the field mode and the laser atoms, e.g., due to the transmissivity of the mirrors. To put it another way, κ_λ is the decay constant of mode λ without laser activity. The constant γ describes the damping of the freely oscillating atomic dipole due to the interaction of the atoms with their environment, and $\gamma_{\|}$ refers to the damping of the atomic inversion due to incoherent decay processes such as non-radiative transitions (e.g., by emitting energy in the form of lattice vibrations or, quantum physically, 'phonons') or spontaneous emission.

13.3.3 Finding the System Dynamics

Now the aim of laser theory is to solve the above system of coupled differential equations, but this is impossible using conventional methods of fundamental physics. The crucial starting point for tackling this task is the empirical fact that there is a hierarchy of time scales, or speeds, for the relevant processes.[8] The characteristic time scales for the dynamics of the field modes b_λ and of the inversion d_μ are much longer than the time scale for the dynamics of the atomic polarization α_μ. This fact can be expressed in terms of inequalities for the characteristic time scales, or alternatively for damping constants (the reciprocals of the time scales):

$$\begin{gathered} T_b \gg T_d \gg T_\alpha \\ \kappa_\lambda \ll \gamma_{\|} \ll \gamma. \end{gathered} \tag{13.7}$$

[8] Hillerbrand (2015), Sect. 13.3.2 of this book, discusses this separation of time scales in the more general context of scale separation and its impact for the feasibility of micro-reduction.

This means that the atomic polarization α_μ (connected to the T_α, or the damping constant γ) reaches its equilibrium value faster than d_μ, and d_μ in turn faster than b_λ, where this equilibrium value of α_μ is—due to the coupling of the differential equations through the non-linear terms—determined by the slower quantities b_λ and d_μ.

The hierarchy of process speeds has an extremely important consequence for the solution of our system of differential equations: certain slow quantities, the so-called *order parameters*, can be treated as constant in time in comparison to the much faster changes in other quantities. While the order parameter, here the field mode b, arises internally through the radiation of all the atoms, the *control parameter* can be adjusted or controlled externally, e.g., by energy supply. In the following description I will provisionally use the language of *synergetics*,[9] which I will scrutinize in the next section. Since the field modes have the longest time scale, one particular b_λ wins the competition and dominates the beat, so to speak. Consequently, there is only one basic mode in the resonator (i.e., symmetry breaking[10]) and one can drop the index λ in the differential equations (single mode case). The next step consists in the formal integration of the differential equations for α_μ:

$$\alpha_\mu(t) = \int_{-\infty}^{t} f_\mu(\tau) d_\mu(\tau) b(\tau) d\tau + \widehat{\Gamma}_\mu(t). \tag{13.8}$$

Note that this step does not yet get us very far since $d_\mu(t)$ and $b(t)$ are not given explicitly, but only implicitly determined by the above differential equations. $\widehat{\Gamma}_\mu(t)$ denotes the result of an integration, and for the following analysis it is not important to know it in any detail. The same applies to the term $f_\mu(\mathrm{t})$.

Mathematically, the following pivotal step is based on the hierarchy of time scales. Since the slower parameters $d_\mu(t)$ and $b(t)$ can be viewed as constant (in time), they can be pulled out of the integrand so that one gets

$$\alpha_\mu(t) = d_\mu(t) b(t) \int_{-\infty}^{t} f_\mu(\tau) d\tau + \widehat{\Gamma}_\mu(t), \tag{13.9}$$

where the integral is solvable in an elementary way. Put in the language of *synergetics* again, this so-called adiabatic approximation means that the atoms "follow

[9] In the 1970s Hermann Haken established the interdisciplinary approach of *synergetics* by transferring certain general insights that he had gained in his work on laser theory (see Haken 1983). Synergetics is one of a few very closely related theories of self-organization in open systems far from thermodynamic equilibrium.

[10] The predominance of one particular mode throughout the entire laser defines a ground state that no longer exhibits the symmetry of the underlying fundamental laws. These laws thus have a hidden symmetry that is no longer visible in the actual state of affairs, i.e., it is "spontaneously broken".

the commands" of the order parameter. The mathematical result of this crucial step is that d_μ is eliminated from the system of differential equations as an independent variable. In other words, d_μ is "enslaved" by $d_\mu(t)$ and $b(t)$. The following steps implement the same procedure for $d_\mu(t)$ and $b(t)$. The final result is *one* equation for *one* variable, namely b, the order parameter. In this way it is possible to solve the seemingly intractable system of differential equations for laser light dynamics. Physically, to cut things short, the resulting dominance of the variable b explains why we get laser light with its outstanding properties such as (almost) monochromaticity, i.e., light with a single pure colour. In the next section, I will spell out in detail why this procedure for explaining the onset of laser light does in fact give us a *mechanistic* explanation.

13.3.4 Why Quantum Laser Theory is a Mechanistic Theory

As promised at the outset, I intend to show that the quantum theory of laser light fulfills all the requirements for a mechanistic explanation. In order to have a clear standard of comparison I use, as introduced above, the characterization by Bechtel and Abrahamsen (2011, p. 258), according to which the core ingredients of a mechanistic explanation are "(1) the identification of the working parts of the mechanism, (2) the determination of the operations they perform, and (3) an account of how the parts and operations are organized so that, under specific contextual conditions, the mechanism realizes the phenomenon of interest". I will proceed in two steps. In this section I will show that a first survey of quantum laser theory allows us to identify all three ingredients of a mechanistic explanation. To this end I will commence by comparing quantum laser theory with its semiclassical predecessor, which will help us to identify the dynamical structures of the laser light mechanism in the quantum treatment. In the second step (Sect. 13.4), I will discuss, and dissolve, a number of worries that seem to undermine a mechanistic reading of quantum laser theory.

Strikingly, the laser equations in a full quantum physical treatment are formally almost identical with the basic equations of the semiclassical laser theory. They can be understood and solved in close analogy with the semiclassical case. Even if one describes everything in terms of quantum physics and includes all the complexity of the situation, the resulting behavior does not change fundamentally in many respects. It just involves a certain number of corrections. But what does this tell us? Despite their remarkably congruent results, it seems that semiclassical and quantum laser theory cannot be taken equally seriously. Semiclassical theories are generally considered to have a dubious status. If QM is true and universally valid, then semiclassical laser theory is, strictly speaking, simply wrong.[11] It is only a very helpful approximation (see Norton 2012), but not the true story. However, in the context of my investigation, I want to make the following claim: the fact that semiclassical laser theory gets so many things right only shows how much classical mechanistic modeling survives in the quantum mechanical explanation.[12]

Since the continuity from the semiclassical reasoning to the quantum treatment refers in particular to the essential interactive processes that produce laser light, this means that, insofar as semiclassical laser theory is mechanistic, so is quantum laser theory. To make this point there is no need to go as far as saying that (semi-) classical reasoning is indispensable for a full understanding of quantum phenomena.[13] Neither is it necessary to claim that purely quantum mechanical explanations are inferior to (semi-) classical explanation in at least some respects, in particular concerning the dynamical structure that is responsible for the phenomenon to be explained.[14] All that is needed in the context of my study is the fact that there are

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[11] Moreover, in semiclassical laser theory, not everything is correct. For instance, below a certain threshold, lasers emit conventional lamp light. Semiclassical laser theory cannot accommodate this fact.

[12] Cartwright (1983) exploits this similarity in a different way. According to her reading, the quantum physical and the semiclassical approach offer two different theoretical treatments, while they tell the same causal story. And since we thus have different theoretical treatments of the same phenomenon, the success of these explanations yields no evidence in favour of a realistic interpretation of the respective theories. Morrison (1994) objects to Cartwright's claim that the fate of the theoretical treatments is a supposedly unique causal story, saying that it is *not* unique. A closer survey of laser theory reveals that "there are also a *variety of causal mechanisms* [my emphasis, MK] associated with damping and line broadening" (Morrison 1994). Consequently, one has to look for something else that the different approaches share. Morrison argues that *capacities*, as introduced in Cartwright (1989), may do the job. However, as she then shows, there is also an insurmountable obstacle for telling a unique causal story in terms of capacities, if one understands capacities as entities in their own right. Against such a Cartwrightian reification of capacities, Morrison argues that, if one wants to describe laser theory in terms of capacities, there is no way around characterizing them in relational terms. Eventually, this could give us a unique causal story, albeit without any additional ontological implications about capacities as entities in their own right. While I think that Morrison's reasoning is generally correct, I think there is an alternative to saying that capacities can only be characterized in relational terms. I claim that the causal story of laser light is best caught in terms of mechanisms. In the context of mechanisms, it is much more obvious that we don't need, and should not reify causal powers, because the crucial thing is the interactive, i.e., causal organization of the system's parts.

[13] This is what Batterman (2002) claims: "There are many aspects of the semiclassical limit of quantum mechanics that cannot be explained purely in quantum mechanical terms, though they are in some sense quantum mechanical" (p. 109). […] "It is indeed remarkable how these quantum mechanical features require reference to classical properties for their full explanation. Once again, these features are all contained in the Schrodinger equation—at least in the asymptotics of its combined long-time and semiclassical limits—yet, their interpretation requires reference to classical mechanics" (p. 110).

[14] Bokulich (2008) refrains from some of the stronger claims by Batterman arguing that "one can take a structure to explain without taking that structure to exist, and one can maintain that even though there may be a purely quantum mechanical explanation for a phenomenon, that explanation —without reference to classical structures—is in some sense deficient" (p. 219); […] semiclassical

structural similarities in the way the dynamics is modelled in the (semi-) classical approach on the one side and the quantum treatment on the other.

So how then are the three requirements for a mechanistic explanation met by quantum laser theory? In order to arrive quickly at a comprehensive picture, I begin with a very brief account, which will be defended in the next section. First, the working parts of the mechanism are the atoms and the field modes. Second, the operations they perform are specified by those parts of the differential equations that only refer to the variable whose dynamics is determined by the differential equation. Third and finally, the account of how these parts and operations are organized so that they produce the phenomenon of interest is given (or rather completed) by the coupling between the different variables in the system of differential equations, together with the crucial observation about the vastly different process speeds (the scale separation in Hillerbrand's terminology). The "specific contextual conditions" are the various specifications of the setup. In the following section I will discuss and dispel a number of objections that might be brought against this identification of the three key elements of a mechanistic explanation in quantum laser theory.

13.4 Potential Obstacles for a Mechanistic Reading

Quantum laser theory as presented above is the full quantum version of a complex systems explanation for a phenomenon concerning the light field which, under certain conditions, arises in a laser. This somewhat cumbersome formulation is meant to comprise all three elements in the explanation of laser light that could block a mechanistic reading. First, it treats the laser as a *complex* system; second, it is a *field* theoretic explanation; and, third, it rests on *quantum* theory with its various differences from classical mechanics. For each of these three potential obstacles to a mechanistic reading, I want to concentrate on that aspect that seems most relevant to me, where the second and the third points are connected.

13.4.1 Is "Enslavement" a Non-mechanistic Concept?

The first potentially problematic point in the above argumentation that quantum laser theory offers a mechanistic explanation of laser light is concerned with the fact that the laser is treated as a complex system.[15] More specifically, the enslavement principle, which I have, following Haken, provisionally employed in Sect. 13.3.3,

(Footnote 14 continued)
explanations are deeper than fully quantum mechanical explanations, *insofar as* they provide more information about the dynamical structure of the system in question than the quantum calculations do" (p. 232). However, in the present context even these weaker claims are not needed.

[15] In Kuhlmann (2011) I deal with the general question of whether complex systems explanations can be understood as mechanistic explanations.

could be incompatible with a mechanistic reading. Thus we need to discuss the exact explanatory and ontological status of this principle. The concept of enslavement generalizes the notion of the order parameter that was introduced with the Ginzburg-Landau theory of superconductivity in the 1950s.[16] The core idea is that the fast parameters are "enslaved" by one (or a few) slow 'order parameter(s)'. For the laser, the field mode b is the order parameter, i.e., the enslaving variable. The order parameter is a quantity that refers to the whole composite system and which arises by the joint action of the component parts. At the same time, the order parameter has, or seems to have, a feedback on what these parts do. Once a macroscopic mode has developed in the laser, the emission behaviour of the single atoms is—due to the broken symmetry—no longer as free as it was before. In synergetics, this fact is expressed by saying that the macroscopic mode dominates or "enslaves" all the component parts.

If this causal language is interpreted realistically it means that a higher-level entity has some kind of autonomous causal power. However, such strong conclusions don't seem to be sustained by the theory. For instance, in laser theory, talk of an order parameter that enslaves the behaviour of the component parts is an unwarranted causal description of a mathematical procedure, because there is no reason why it should represent a corresponding physical process. Arguably the most detailed critique of the far-reaching claims of synergetics concerning the ontological status of enslavement has been put forward by Stephan (1999), Chap. 18. He argues that the crucial significance of the order parameter in synergetics is merely a matter of description: only a descriptive thesis about the *compressibility of information* is warranted, namely that the system behaviour can be adequately described by one or a few order parameters without any need to specify the behaviour of all individual parts. However, this compressibility of information doesn't licence a *compressibility of causal factors*, i.e., the different and much stronger claim that the order parameter is a causal agent in its own right, which determines the behaviour of the system's parts. In more abstract terms, Stephan diagnoses a logical fallacy of the type post hoc, *ergo propter hoc*: the fact that focusing on the order parameters allows us to predict the behaviour of the system does not imply that the order parameter causally determines the system with all its parts. The implausibility of rating order parameters as causal factors becomes most obvious by looking at applications of synergetics in the social sciences: the work climate, Stephan says (p. 237), doesn't enslave the behavior of the clerks because the work climate doesn't do anything at all.

As Hillerbrand (2015), Sect. 13.3.2 of this book, puts it, the "methodology known as the 'slaving principle' […] allows one to drastically simplify the micro-reductionist description". However, this doesn't imply that the employed order

[16] The Ginzburg-Landau theory was initially a phenomenological theory that analyzed the occurrence of superconducting phase transitions by general thermodynamic arguments without using a microscopic underpinning (as later supplied by the Bardeen-Cooper-Schrieffer theory). See Morrison (2012) for a detailed discussion of the philosophical implications concerning emergence in particular.

parameter thereby becomes an autonomous higher-level entity that defies a mechanistic description. In conclusion, I want to claim that theories of self-organizing systems, such as synergetics,—restricted to the justified descriptive reading of the slaving principle and thus refraining from taking the causal metaphors for the order parameter for real—explain the formation of system-wide patterns in terms of the endogenous interactions of the system's parts (hence *synergetics* for "working together"), and this fits nicely with the idea of mechanistic explanations.

13.4.2 Why Parts of a Mechanism don't need to be Spatial Parts

The second potential problem for a mechanistic reading of quantum laser theory is that the "parts" in the laser mechanism are not parts in the sense of spatiotemporal things. One source of this problem, which already applies to semiclassical laser theory, is that field modes are not individual things. For example, they can overlap and they cannot be traced through time. The other source of the problem is that we are dealing with quantum objects, which in general cannot be distinguished spatiotemporally.[17] Often, many quantum objects occupy the same spacetime region. Let us explore these potential problems a bit more closely.

One assumption in my above argument in favor of a mechanistic reading of laser theory is that field modes, or light quanta, are entities[18] that can feature as parts in a mechanism. But is it really sensible to understand modes of a field (classically possible states of oscillation) as parts? After all, different field modes can occupy the same region of spacetime. However, in the face of the wave-particle dualism, it seems just as legitimate or illegitimate to view light quanta as parts as it is to view, say, electrons as parts.[19] But this brings us to a more general point: What in general counts as a part in a mechanism? Rather than solving the problem of whether light quanta can be rated as parts, the reference to the wave-particle dualism shows that electrons and atoms may also be infected by the same problem.

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[17] See Kuhlmann and Glennan (2014) for a more general and comprehensive discussion of whether quantum physics undermines the mechanistic program.

[18] As it is very common in ontology, I use the expression 'entity' as the most neutral ontological term, covering everything that exists from conventional things like dogs to properties and states-of-affairs. I only mention this because, in MDC's account of mechanisms, the term 'entities' is used more specifically in the sense of things or 'substances'.

[19] Falkenburg (2007, Chap. 6) explores the part-whole relation for quantum systems in more detail. She argues that the sum rules for conserved quantities such as mass-energy, charge, and spin are crucial for determining what we should rate as the constituents/parts of matter. On the basis of this criterion she draws a positive conclusion regarding the question of whether even the quanta of interaction fields such as the gluons in the quark model can feature as parts of quantum systems.

In the following I want to argue that it is a classical prejudice that *parts* of a concrete thing must always be spatially distinguishable entities.[20] In laser theory, field modes are sufficiently specified to function as independent *parts* that interact with the laser-active atoms. The field modes are not specified spatially, but with respect to their causal role. But that is enough for a mechanistic explanation to work. The decomposition of a compound system into components is a pragmatic matter that is ultimately justified by its explanatory success.[21] And in the case of the laser, understanding field modes as parts does the trick.[22] In many cases, it has no relevance where and even whether, say, objects O_1, O_2, and O_3 are located. What really matters is that, for example, (objects of type) O_1 is/are influenced by the behavior of (objects of type) O_3 in a specific way, while being unaffected by what (objects of type) O_2 does/do in the meantime. This situation is very common in complex systems research, where it is often only specified how the components are causally organized, whereas their spatial organization, if there is any, is left completely open.[23]

When we take field modes as parts of the laser mechanism, we stay very close to the mathematical treatment of lasers. Mathematically, field modes don't play any different role to laser-active atoms. Both are described by their own differential equations (which are coupled with each other). But this may be too much of a reification of field modes. Alternatively, it seems that one could stay with the conventional view and take the laser-active atoms as the crucial parts of the laser mechanism and the electromagnetic field as the interaction between the parts of the mechanism. In this case there would no longer be any need to relax the notion of parts by including entities that are not spatiotemporally distinguishable. However, I think it is nevertheless more appropriate also to treat field modes as parts of the laser mechanism. On the one hand, I argued above that the order parameter, i.e., the field mode $b(t)$ from above that "wins the battle"—because due to its comparatively long characteristic time scale for reaching its equilibrium value it can "enslave" the faster quantities—is no autonomous causal agent (see Sect. 13.4.1). On the other hand, the initial differential Eq. (13.3) apply to the whole spectrum of quantized field modes, which do real causal work. After all, "laser" is an acronym for "light amplification by *stimulated emission* of radiation", i.e., it is crucial for the emergence of laser light that the light field inside the laser cavity *causes* the atoms to emit radiation at a certain wavelength. And, I want to argue, it is most natural to treat those entities that do real causal work in a mechanism as *parts* of that

[20] I want to mention briefly that in current ontology there is a popular approach, namely trope ontology, which analyses things as bundles of copresent properties (understood as tropes, i.e., particularized properties). And many trope ontologists argue that properties should be seen as parts, although they can occupy, as constituents of one bundle, the same spacetime region.

[21] As an aside, Bechtel and Richardson (2010) distinction of decomposition *and* localization already implies that successful decomposition does not automatically lead to localized components.

[22] See Healey (2013) for similar considerations, but with a diverging aim.

[23] See Kuhlmann (2011) for detailed examples.

mechanism. Thus, in conclusion, I think it is more appropriate to rethink the notion of parts, and rate field modes as parts of a mechanism.

One last possible objection against field modes as parts is that their number is by no means constant, in contrast to the number of atoms. But this is not unusual in complex systems. We can clearly have mechanisms in complex systems where the parts can vary drastically. For instance, in convection cells of heated viscous fluids we can easily add and release molecules of the appropriate kind of liquid without changing or even stopping the workings of this self-organizing mechanism. Analogously, the changing number of field modes is no argument against rating them as parts.

13.4.3 Why Quantum Holism doesn't Undermine Mechanistic Reduction

The third potential obstacle for a mechanistic reading of quantum laser theory is that quantum holism may prevent us from decomposing the laser into different interacting parts, as is required for a mechanistic explanation. In general, the photons and atoms in a laser will be entangled with each other. Due to this entanglement, the subsystems (i.e., photons and atoms) are not in determinate states,[24] even if the whole laser is taken to be in a determinate state. Note that non-determinateness of properties differs from non-determinateness of states. In a sense, the latter is worse than the former. While the non-determinateness of properties can be dealt with in terms of dispositions or propensities, non-determinateness of states seems to pose a more serious threat to the applicability of the mechanistic conception in the quantum realm, because it may foreclose the ascription of properties to *distinct parts* of a compound system—no matter whether these properties are determinate (or 'categorical') or only probabilistically dispositional. To put it another way, I can't say everything relevant about one given quantum object without having to say something about other quantum objects, too, and this applies not just to their mutual spatiotemporal relation. This non-separability of quantum states is often called 'quantum holism'. Here we may have a strong form of emergence, because the reason why a given compound system (with entangled subsystems) is in a certain determinate or 'pure' state,[25] namely in this case a certain superposition, cannot be

[24] States comprise those properties that can change in time, like position, momentum, and spin (e.g., up or down for electrons). Besides these changing properties, there are permanent properties, such as mass, charge, and spin quantum number (e.g., electrons have the spin quantum number ½, which allows for two possible quantized measurement results, up or down, for any given spin direction).

[25] A pure state is represented by a vector in a Hilbert space. The contrast with a pure state is a mixed state, which can no longer be represented by a single vector. A mixed state can describe a probabilistic mixture of pure states.

explained in terms of determinate states of its subsystems.[26] In other words, the entangled parts of a compound system in a determinate state can no longer themselves be in determinate states. On this basis, Hüttemann (2005) argues that "synchronic microexplanations" do in fact fail in the realm of quantum physics, due to the notorious holism of entangled quantum systems.

Since the mechanistic conception of explanation is based on the reductionist idea that the behavior of compound systems can be explained in terms of their parts, it may look like the failure of reductionism due to the non-separability of quantum states could infect the mechanistic program, too. However, this is not the case because mechanistic explanations are concerned with the *dynamics* of compound systems and not with the question of whether the states of the subsystems determine the state of the compound system at a given time. In Hüttemann's terminology, the issue is diachronic and not synchronic microexplanations. As we have seen, in quantum mechanics the dynamics of a compound system is determined its by the Schrödinger equation—or the Heisenberg equation—where the crucial Hamiltonian that actually breathes life into the Schrödinger dynamics is the sum of all the "little Hamiltonians" for the system's parts and the interactions. Specifically, in quantum laser theory, in order to determine how the compound system evolves in time, all we need to know are the Hamiltonians for the subsystems, i.e., roughly the atoms, the light field, and the heat baths, and the Hamiltonians for their respective interactions. These Hamiltonians are simply added up. There are no tensor products for Hamiltonians and neither is there any entanglement of Hamiltonians.[27] In conclusion, one can say that, although quantum holism does mean that even the fullest knowledge about the parts of a given whole doesn't give us full knowledge about this whole, quantum holism does not undermine the mechanistic program of explaining the *dynamical* behavior of a compound system in terms of the interaction of its parts.

13.5 The Scope of Mechanistic Explanations

One could wonder now whether the requirements for something to be a mechanistic explanation are so general (abstract, loose) that practically any scientific explanation would count as mechanistic. Don't scientists always analyze complex phenomena, which are not yet understood, by reference to some kind of more basic items (call them 'parts') and then show how these items are related to one another (interact) to account for (bring about) the phenomenon in question? Well, 'Yes' and 'No'. The answer seems to be 'Yes', when scientists claim to have an explanation for some

[26] See Hüttemann (2005), who offers a very convincing study of the extent to which emergence occurs in QM, and correspondingly, 'microexplanations' fail vis-à-vis QM. Although Hüttemann's focus differs from that of the present investigation, his arguments are nevertheless relevant, with suitable adjustments.

[27] Note that this doesn't preclude the possibility of emergence in the sense of a failure of synchronic microexplanations.

dynamical phenomenon or law. In these cases they do in fact very often proceed in a mechanistic fashion. And one could even ponder the following claim: to the extent that science explains it does so mechanistically, and this fact is not undermined by QM. But this claim is arguably too strong. I don't want to claim that any scientific explanation is mechanistic, but rather that mechanistic explanations do not become impossible in the realm of QM, and are in fact widespread even there. So the answer is also 'No', since not every explanation or reasoning in science is mechanistic.

So why does quantum laser theory give us a mechanistic explanation? I think in this case one has to show in particular that the following non-trivial requirement is fulfilled: an account of how the components of the system interact in order to produce the phenomenon to be explained must lie at the core of the explanation. Note that this requirement for a mechanistic explanation is not fulfilled by the mere fact that an explanation makes reference to component parts and the way these parts are related to one another, as can be seen by looking at an example of a non-mechanistic explanation. In his famous derivation of black body radiation Planck (1901) calculates the entropy of a system of oscillators which he assumes to make up the walls of the cavity. This explanation refers to component parts, namely the atoms in the walls of the cavity, and to a certain extent it makes an assumption about how these parts are related to one another, but the interrelation of the constituent parts plays no important role in the explanation. Since it was already known in the nineteenth century that the spectral distribution of black body radiation is independent of the material and even the composition of the given body, one could to a certain extent assume just any kind of underlying processes in order to make the calculations as manageable as possible.

Nuclear physics is another context where mechanistic and non-mechanistic explanations coexist. Many explanations in nuclear physics are based on one of two very different models, namely the liquid drop model and the nuclear shell model. The liquid drop model treats the nucleus as an incompressible drop of nuclear fluid, and with this assumption it is possible, to a certain extent at least, to explain the energy as a consequence of its surface tension. Such an explanation is clearly not mechanistic. The nuclear shell model, on the other hand, describes the structure of a nucleus in terms of energy levels.

Another group of non-mechanistic explanations in physics concerns analyses that abstract completely from any processes that produce the phenomenon to be explained. In this group, I see for instance derivations and motivations based on conservation laws, symmetry considerations, and dimensional analysis.[28] One very simple example of the first kind is the calculation of the velocity of a falling object based on the transformation of potential into kinetic energy due to energy conservation, without any kinematical description whatsoever. Moreover, due to Noether's theorem, conservation laws are closely linked to invariances under

[28] Recently, Reutlinger (2014) has argued that renormalization group methods also yield non-causal explanations—and a fortiori non-mechanistic ones—not because of the irrelevance of micro-details, but because the mathematical operations involved are not meant to represent any causal relations.

certain symmetry transformations which can often be used in a very elegant way. Finally, a beautiful example of dimensional analysis is the derivation of the period of oscillation of a harmonic oscillator purely by considering the potentially relevant quantities and looking for a combination of these quantities that has the correct dimension—it turns out there is just one. [29]

Still another example of a non-mechanistic type of explanation is the derivation of special laws from more general laws in the covering law fashion. For instance, Kepler's laws for elliptic orbits of planetary motion can be explained using Newton's laws and certain approximations. In this case the two-body problem of the sun and a planet can be reduced to a one-body problem with a central force field around the center of mass of the two bodies. The reason this can be done is that the details of the interaction between the sun and the planet are totally irrelevant. And for this same reason, it should not be considered a mechanistic explanation. Yet another example of law-based non-mechanistic explanations are derivations based on thermodynamic laws like the ideal gas law. In these cases we do not refer to any causal mechanisms, but only state how certain macroscopic quantities are related to each other.

Finally, mechanistic explanations do not work for the simplest cases, such as the attraction of masses or charges in classical mechanics and electrodynamics, or the quantum harmonic oscillator and the behaviour of an electron in a magnetic field. This indicates that mechanistic explanations are not ruled out by the corresponding theory, but rather that some phenomena cannot be explained mechanistically because the system under consideration is either too simple or too fundamental. Thus, assuming that there is a bottom level in each theory, mechanistic explanations must come to an end somewhere, no matter whether we are dealing with quantum or classical physics.[30] Therefore, in this respect the main contrast is not classical

[29] See Sterrett (2010) for a philosophical analysis of the role of dimensional analysis in science.

[30] So can EPR style correlations also be explained by quantum mechanics? Imagine someone performs spin measurements on separated electron pairs that were emitted from a common source. Further imagine that our observer realizes that there are certain regularities in the results of two spin measurement devices. Each time she gets a spin up result in measurement device 1, she gets spin down in measurement device 2, and vice versa. Naturally, our observer assumes that there is a common cause for the correlations. By analogy, if you have pairs of gloves and each pair gets separated into two distant boxes, you always find a right glove in box 2, if you found a left glove in box 1. However, one finds that the electron pairs are correlated in a more intricate way: if you rotate the orientation of the spin measurement devices, you find the same kind of spin correlations again, even if you rotate by 90°. Since an electron cannot have a definite spin with respect to two mutually perpendicular orientations at the same time, the common cause explanation breaks down for the correlated spins of our electron pairs. In contrast, with quantum mechanics, it is possible to derive EPR style correlations from the basic axioms, namely from the unitary time evolution of states given by the Schrödinger equation and the resulting principle of superposition. But does this mean that EPR style correlations are explained? One could argue that in the framework of standard quantum mechanics, EPR style correlations are explained in a covering-law fashion. However, there is no explanation for why they come about, no causal story, and in particular no mechanistic story. Only particular interpretations or modifications of QM, such as Bohmian QM or the many worlds interpretation, may supply something like a mechanistic explanation.

mechanics versus quantum mechanics, but rather composite/organized systems vs. fundamental building blocks.

But the initial question may not yet be fully answered: Under which circumstances would laser theory not count as a supplying a mechanistic explanation of laser light? If one were to take Haken's quasi-metaphysical talk about the enslaving principle as an ontological commitment, then mechanistic explanation would become impossible to defend. While Haken has produced great achievements in laser theory, there is, as a consequence of Ockham's razor, no need to follow his metaphysical speculations, as we have seen in Sect. 13.4.3.

13.6 Conclusion

Mechanistic explanations are widespread in science, with the notion of 'mechanism' providing the foundation for what is deemed explanatory in many fields. Whether or not mechanistic explanations are (or can be) given does not depend on the science or the basic theory one is dealing with, but on the kind of object or system (or 'object system') one is studying and on the specific explanatory target. Accordingly, there are mechanistic explanations in classical mechanics, just as in quantum physics, and also non-mechanistic explanations in both of these fields. So not only are mechanistic explanations not corrupted by the non-classical peculiarities of quantum physics, but they actually constitute an important standard type of explanation even in the quantum realm.

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