Particles, Statistics and Identity in Quantum Theory

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Abstract

According to what is known as the Received View, quantum particles of the same kind have no identity. Quantum statistics provides one of the main arguments for this position, namely that permutations of quantum particles of the same kind do not result in new particle configurations, while permutations of classical particles always do. According to the Received View, there is therefore a sharp contrast between classical and quantum particles. In this article, we criticise the Received View in general and the argument from statistics in particular. We discuss and defend an alternative view, according to which particles in modern physics are not fundamental but rather emergent entities. Accordingly, classical particles are limiting cases of emergent quantum particles, so that the difference between quantum and classical particles is only gradual. We discuss recent objections to this alternative approach.

Keywords: Indistinguishable quantum particles; Identity; Received View; Alternative View; Quantum statistics.

1. Introduction

In the nineteenth and early twentieth centuries, physicists discovered that the building blocks of matter break down into species, such as electrons, protons and neutrons. Particles of the same kind were found to possess exactly the same intrinsic properties, characteristic of their species. For example, all electrons have exactly the same electrical charge and (rest)mass. The twentieth century also showed that a new mechanics was needed to describe these submicroscopic entities: quantum mechanics. This new theory radically changed long-held ideas about how particles behave and even about what particles are. In particular, the idea that particles are individual tiny clumps of matter that can always be kept apart and tracked over time has been seriously challenged. But before going into the reasons for these doubts, it is useful to look at how particles are treated in classical mechanics.

Consider a number of classically described electrons, all with the same charge and mass. Classical particles always occupy well-defined spatial positions and, as time passes, follow well-defined paths in space (or remain at rest in the same place). Moreover, in classical mechanics there is a principle of “impenetrability”, which says that two particles can never be in the same position. So, classical electrons (often idealized as point particles, but they could also have a finite size, which must then be the same for all electrons) are always distinguishable from each other by virtue of their different spatial positions and their different histories, i.e. the spatial paths (trajectories) they take. Different paths generally correspond to different speeds, so the speed of different electrons will usually not be the same either. Thus, while classically described electrons have the same intrinsic properties, there are also "extrinsic" properties that differ from electron to electron and define their individual classical mechanical state (x, v)----the combination of position and velocity, which in the case of deterministic evolution also determines their history. If evolution is not deterministic, for example due to random forces acting on the electrons, each electron still follows a continuous path so that it can be followed in time.

Based on their extrinsic physical differences, it is possible to name or number classical electrons in a physically meaningful way. Suppose we have two electrons in different places, call them electron 1 and electron 2. What happens if we swap the two electrons, letting electron 1 take the place of electron 2 and vice versa? To answer this question, it is important to be precise regarding the kind of swapping operation we have in mind. We could think of a physical exchange process, where each of the electrons is transported to the place of the other. In this case, the permutation leads to a new situation, in the sense that it is an objective physical fact that the electron that was first in position 1 now resides in position 2. Admittedly, this change cannot be verified at the instantaneous two-particle state, but a film of the exchange process would conclusively demonstrate the objectivity of the difference from the original situation.

Another interpretation of swapping that frequently appears in the literature, especially in philosophical discussions, is the *permutation of particle identities*, without any physical transport. In this case, the identity of electron 1 is imagined to instantaneously replace the identity of electron 2 and vice versa. To discuss this further we obviously need to be more precise about what we mean by the identity of a particle.

One possibility is to associate the identity of a particle with a supposed individuating principle that resides within the particle independent of its physical properties. This is the idea behind haecceities, "primitive thisnesses", "quiddities", or underlying quality-free substances to which physical properties are imagined to attach. If such a concept of identity is assumed, for example by endowing each electron with its own primitive thisness, the permutation of identities can be represented by simply exchanging the labels 1 and 2 while all physical properties at both electron histories remain unchanged. The permuted situation is then not physically distinguishable from the original one---not even by a film, since no physical change accompanying the permutation ever occurred.

These non-empirical notions of particle identity and particle exchange are inconsistent with the methodological principle of natural science that conceptual distinctions should not be introduced if they are in no way related to physically determinable differences. In what follows, we will therefore adhere to a concept of identity consistent with Leibniz's Principle of the Identity of Indiscernibles, in which "indiscernible" is understood as indistinguishable via *physical differences*.

In this article we accordingly assume that it is only justified to speak of a multiplicity of things if it is possible in principle to distinguish these things by *physical* means, and we will only briefly refer to interpretations of classical and quantum mechanics that appeal to haecceistic individualising principles. This is not a lacuna, for it turns out that such non-empirical individualising principles are unnecessary, both in classical and quantum physics. As we will demonstrate, all empirical results, including those of statistical experiments, can be explained by paying attention to physical characteristics of the experiments in question.

In usual presentations of quantum mechanics there is as much talk about particles as in classical mechanics. However, in quantum mechanics particle states are represented entirely differently from the combination of physical quantities such as (x, v). Instead, a wave function is used, i.e. a function that assigns a complex number to each point in space. The square of the absolute value of that number, $|\psi(x)|^2$, represents the probability of finding the particle at position x when measured[1]. The description by means of a function extended in space by itself already raises questions about the nature of quantum particles, but we want to focus here on the problems that arise when describing more than one quantum particles of the same kind (such as electrons), and in particular on whether such particles are physically distinguishable and possess a Leibnizian identity (i.e. an identity determined by individuating physical features).

Central to the quantum theory of particles of the same kind is the symmetry postulate, which says that the overall wave function of a many-particle system must be either symmetric or anti-symmetric. For the particles that build up matter, fermions, anti-symmetry applies; for the particles that transmit forces, bosons, the wave function must be symmetric. We will deal here mainly with fermions (electrons, protons, neutrons, etc.). Suppose we imagine two electrons, one represented by wave function $\psi(x)$ and the other by $\phi(x)$. It then seems natural to assume that the total wave function looks like $\psi(x_1).\phi(x_2)$, the simple combination of the two individual descriptions. However, the anti-symmetry postulate requires the following form: $\frac{1}{\sqrt{2}}\{\psi(x_1).\phi(x_2) - \phi(x_1).\psi(x_2)\}$.

Now, a total wave function of the form $\psi(x_1).\phi(x_2)$ would be consistent with the idea that each electron has its own individual wave function, namely electron 1 wave function $\psi(x)$ and electron 2 wave function $\phi(x)$. But as just explained, quantum mechanics demands the anti-symmetric state, and in that state the subscripts 1 and 2 are both "equally distributed" between $\psi(x)$ and $\phi(x)$. A more precise mathematical analysis confirms that the two single-particle states associated with 1 and 2, respectively, and derivable from the two-particle state $\frac{1}{\sqrt{2}}\{\psi(x_1).\phi(x_2) - \phi(x_1).\psi(x_2)\}$, are indeed exactly the same---it is, in bra-ket notation, in both cases the "mixed state" $\frac{1}{2}(|\psi\rangle\langle\psi| + |\phi\rangle\langle\phi|)$. It follows that if the subscripts 1 and 2 label single electrons, these electrons must be in exactly the same quantum state, a mixture with equal proportions of ψ and ϕ.

This result suggests that quantum particles of the same kind not only share their intrinsic properties, but exhibit a much stronger form of indistinguishability: all their state-dependent extrinsic properties appear also to be the same, so that no physical

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[1] There are good reasons to think that a quantum particle does not have a well-defined position prior to a measurement, so that a position measurement does not simply remove our ignorance of the position. We stay here within this standard idea, according to which the quantum mechanical description with wave functions is complete, and thus do not consider interpretations that supplement the quantum formalism with additional quantities (such as Bohm's theory).

experiment could ever distinguish them. Physical Leibnizian particle identities are in this case ruled out, and only haecceistic principles remain to substantiate particle identity.

As will be explained and discussed in section 3, the fact that swapping subscripts in (anti-)symmetric two-particle wave functions, or swapping the single-particle states occurring in those wave functions, does not lead to any physical differences, can also be used to mount a *statistical* argument against Leibnizian particle identity. The core idea is as follows. When we flip two classical coins, the outcome Heads-Tails will occur twice as often as the outcomes Heads-Heads and Tails-Tails. This is because, the usual story goes, the coins each have their own identity and can be given a corresponding name, for example 1 and 2. Heads-Tails can thus be realized in two ways, with coin 1 showing Heads or coin 1 showing Tails, respectively. In total, there are consequently four possible different outcomes: both coins showing Heads, both coins Tails, coin 1 Heads and coin 2 Tails, and coin 1 Tails and coin 2 Heads. These four possible outcomes are equally probable if the coin toss is fair. By contrast, in the bosonic quantum case the symmetrisation postulate ensures that there are only *three* possible outcome states, corresponding to Heads-Heads, Tails-Tails, and Heads-Tails, respectively. Now these *three* possibilities should be assigned equal probabilities in a fair toss, so the probabilities are different from the classical ones. These new quantum probabilities are confirmed in certain experiments. In the extensive literature on quantum statistics, this is generally considered conclusive evidence for the absence of identity in "quantum coins." However, in section 3 we will argue that this statistical argument is inconclusive, and that bosons may have an identity, in certain situations, in the same way as classical particles.

For the moment, however, let us go along with the conclusion that quantum particles of the same kind cannot have a physical, Leibnizian identity. In this case, it is possible to preserve the identity of quantum particles nevertheless by appealing to haecceities, which are physically impotent. But there is another way out, less objectionable from a scientific-methodological perspective, namely, by assuming that quantum particles are a completely new kind of entities, unknown in classical physics: entities without identity. This is the central idea of what Steven French and Décio Krause (2006) have called the Received View of quantum particles of the same kind.

This view was elaborated by French and Krause into a formal scheme that deals with objects that cannot be told apart in any way, cannot be given individual names and cannot be labelled. Nevertheless, there can be a well-defined total number of them, which form a collection. But such a collection cannot be an ordinary set as defined in standard (Zermelo-Fraenkel, ZF) set theory, because the elements of a standard set are always at least conceptually distinguishable from each other (each element has the typical property represented by its own singleton set). Décio Krause has therefore designed a logically sophisticated “quasi-set theory”, with axioms different from those of ZF set theory. In this new theory, quasi-sets of indistinguishable elements have a quasi-cardinal, indicating the number of their elements---but these elements cannot be ordered or individually numbered, as this would give them identity. The identity relation “=” is not defined for such elements, so that even the expression “x=x” cannot be written down. Instead of “=” there is only the weaker relation of indistinguishability, “≡”.

In this article, however, we defend an alternative to the Received View and views appealing to haecceities and the like (section 2). We argue that it is not necessary to introduce haecceistic principles, non-standard mathematics or a new logic to deal with "identical particles" in quantum theory. Nor do we need to introduce the metaphysical category of objects without identity. An important theme in our argument is that classical particles can only have a gradual difference from quantum particles: if quantum theory is a fundamental theory that replaces classical mechanics at all levels of complexity (the modern consensus), then classical descriptions should become applicable in limit situations described by quantum mechanics. In other words, classical particles should *emerge* from the quantum description in the classical regime.

Therefore, we must expect that when typical classicality conditions are fulfilled even quantum particles can possess a Leibnizian identity, can be treated using standard ZF set theory, and exhibit patterns of behaviour that are approximately classical. This agrees with the conclusions of our critical discussion, in section 3, of the standard statistical argument for the absence of identity in quantum particles of the same kind. We show in section 3 that this argument is based on question-begging premises, and that the (anti-)symmetric states of identical quantum particles are compatible with classical statistics.

In section 4 we respond to recent objections that claim to show that the identity we attribute to quantum particles is not genuine, but rather a "mock" or "fake" identity that is unable to support the notion of diachronic identity and cannot ground counterfactual statements.

It remains true that under circumstances very different from those in our macroworld, it can be utterly impossible to make physical distinctions that correspond to a plausible division of the physical world into particles. But why would we use a particle ontology in such situations at all? The motivation for introducing the concept of a particle is precisely the possibility of separating and distinguishing elementary entities; if we cannot make the relevant distinctions, that motivation disappears.

The conclusion that we will attempt to establish is that particles are not fundamental but emergent entities and that their identities emerge with them. Even the identity of objects in our everyday macroscopic world can consequently not be fully robust under all possible conditions. After all, if these objects are fundamentally quantum, their very objecthood must be emergent and their properties can therefore only be effectively and approximately classical. The robust notion of identity underlying many philosophical and logical analyses therefore appears to have no exact equivalent in the physical world (section 5). All this can be discussed and analysed within the framework of standard mathematics, ordinary logic and Leibniz's Principle.

2. An alternative to the Received View

French and Krause (2006, p. 143) pithily characterize their Received View in the following way: "Classical particles are individuals but quantum particles are not". In their formal development of the view, in which quasi-set theory replaces ZFU set theory (Zermelo-Fraenkel set theory with "atoms", *Urelemente*), this distinction between classical and quantum is reflected in the axioms. Instead of one kind of *Urelemente*, as in ZF, two kinds of "atoms" are introduced, namely m-atoms and M-atoms (French and Krause 2006, sec. 7.2). The M-atoms are meant to refer to "classical things", for which the identity relation "=" is meaningful; the m-atoms are non-individuals, standing to each other in the relation of indistinguishability "≡" but to which the identity relation "=" does not apply.

We explained the rationale for this set-up in the Introduction, where we also already indicated that this opposition between classical and quantum particles raises a problem. If quantum mechanics is understood as a fundamental theory, which is the present-day standard view, quantum mechanics should be able to reproduce classical descriptions as limit cases. We then expect quantum particles in the classical limit to behave like their classical counterparts. But how is this possible if there is a principled difference between quantum and classical particles? Could it be that in some scenarios, m-particles make a "jump" and thus attain M-status?

To assess the situation, it is helpful to look again at our earlier two-electron wave function of the form $\frac{1}{\sqrt{2}}\{\psi(x_1).\phi(x_2) - \phi(x_1).\psi(x_2)\}$. The main reason for denying electrons individuality in this case is that interchanging the labels 1 and 2 is not associated with any physical difference. As French and Krause (2006, p. 143) put it, "from the point of view of the statistics, the particle labels are otiose." As we have seen, this physical irrelevance of the labels follows directly from the anti-symmetry requirement for fermion wave functions, a fundamental principle of quantum mechanics, which is in no way invalidated or suspended when approaching the classical regime. We can make the wave function undergo all possible interactions, and possibly apply approximation techniques or perform averaging over quantities, but as long as quantum mechanics holds, all physically meaningful quantities remain equally distributed between the labels 1 and 2. It follows that even in the classical limit, these labels remain otiose. But then they cannot be labels of classical particles. Indeed, as discussed in the Introduction, the labels of classical particles correspond to individuating physical particle properties. The identity-less particles of the Received View (m-atoms) can therefore never become M-atoms (classical particles), not even in the classical limit. Thus, the Received View electrons cannot become the electrons of Maxwell's theory, not even approximately.

The origin of this problem is that the correct observation that different labels in the (anti-)symmetric many-particle wave function do not correspond to physical differences, is combined with the (in our eyes objectionable) idea that these labels in one way or another nevertheless function as particle labels---the physical otiosity of the particle labels then motivates the ideas of perfect exchangeability and lack of identity.

The interpretation of the labels as *particle* labels, in (anti-)symmetric wave functions, is known, in the recent philosophy of physics literature, as "factorism" (a term due to Caulton 2014). It may seem a natural, perhaps even self-evident, interpretation. Indeed, in constructing the theory of many-particle systems, the standard way to begin is to consider a particle, particle 1, with its wave function $\psi(x)$ and another particle, particle 2, with a different wave function $\phi(x)$; this conceptual starting point already involves labelled particles. Note, however, that these labels are intended to correlate with physical differences, namely different wave functions. Only later, when completing the theoretical framework of many-particle quantum mechanics, is the anti-symmetry postulate introduced, which almost surreptitiously undoes the correlation between labels and physical differences.

Realizing this, factorism is not as self-evident as it may have seemed at first. Although labels were originally intended to indicate different individualities, they cannot play that role anymore after (anti-)symmetry is imposed. However, the distinctive one-particle wave functions themselves are still present in the overall wave function. In this light, it appears natural to explore the possibility of conceiving not the labels but the different one-particle states $\psi(x)$ and $\phi(x)$ themselves as particle representatives in total states like $\frac{1}{\sqrt{2}}\{\psi(x_1).\phi(x_2) - \phi(x_1).\psi(x_2)\}$.

This is the core idea of the “alternative view” (Dieks 2023b) or “heterodox approach” (French and Bigaj 2024). This alternative arrives at conclusions about particle identity that are quite different from those of the Received View, because its adoption makes it possible---at least in some cases---to characterise quantum particles by individual physical properties (associated with different one-particle wave functions). It is then certainly no longer fundamentally ruled out to distinguish particles of the same kind from each other, and to treat classical particles as boundary cases of quantum particles.

Unorthodox ideas of this kind were developed by various authors (Bigaj 2022; Dieks and Lubberdink 2011,2022; Caulton 2014; Friebe 2014; see also French and Bigaj 2024). The central new idea is that a total wavefunction of the form $\frac{1}{\sqrt{2}}\{|\psi_1\rangle|\phi_2\rangle - |\phi_1\rangle|\psi_2\rangle\}$, where we have switched to the usual representation of quantum states by vectors in a Hilbert space, describes two fermions one of which is characterized by $|\psi\rangle$ and the other by $|\phi\rangle$. These particles are then perfectly distinguishable since the states $|\psi\rangle$ and $|\phi\rangle$ in a total wavefunction of this anti-symmetric form must be orthogonal, as can be easily verified. Indeed, any non-orthogonal components fall away under anti-symmetrisation.

As a concrete illustration, consider two orthogonal states $|\psi\rangle$ and $|\phi\rangle$ that correspond to wave functions differing noticeably from zero only in two spatial regions that are far apart from each other, left and right, respectively. The alternative approach in this case says that there is one particle on the left and one particle on the right. In contrast, *labels* 1 and 2 are each associated with both left and right in the total wave function. So indistinguishable particles corresponding to the labels must each be in exactly the same state, namely half left and half right (a mixed state, as explained in the introduction).

However, if position *measurements* are performed, their results will certainly indicate the presence of exactly one particle in each of the two regions, far left and far right, in accordance with the alternative interpretation we suggested. Quite generally, the alternative view fits well with the way quantum particles are treated in physical practice. In quantum experiments, elementary particles are often individually manipulated and serve as tools for investigating the structure of other particles (for example, by causing them to collide with these other particles). Think of firing individual electrons with the help of an “electron gun”, or think of the protons and neutrons circling in the cyclotron rings at CERN. In none of these cases are quantum particles considered non-individuals.

Theoretically, the alternative approach is supported by results of Ghirardi, Marinatti and Weber (2002), who have shown that the entangled wave functions arising from (anti-)symmetrising product wave functions lack many of the typical non-classical properties that entangled states can generally exhibit (such as Bell non-locality). This confirms that such states can be interpreted as a description of quasi-classical particles, in the sense that the system will manifest itself---in many interactions and measurements---as consisting of entities that can be distinguished from each other on the basis of their single-particle wave functions.

The applicability of a semi-classical picture does not mean that it is impossible to devise experiments that can provide evidence of typical quantum behaviour. This applies even to everyday objects, which in principle are also subject to quantum mechanics. However, in ordinary everyday circumstances extremely sophisticated experiments are needed to demonstrate such quantum effects.

Not *all* anti-symmetric wave functions can be interpreted in terms of semi-classical individual fermions characterized by distinct wave functions. For example, quantum states that are superpositions of anti-symmetrised product states will generally not be anti-symmetrised products themselves. The results of Ghirardi-Marinatti-Weber do not apply to states of that form, and in such cases we generally cannot define particles by associating them with single-particle wave functions (although decoherence processes, to be discussed later, can alleviate this problem in the classical limit). More generally, it appears that the concept of individual particles becomes increasingly problematic as we move further away from the classical regime. When we enter the domain of quantum field theory, we face general theorems proving that localised entities are impossible, so that the existence of anything intuitively close to a classical particle is ruled out at this level of reality. There are several other counter-intuitive results (Fraser 2008, Dieks 2023). For example, particle number is not always a well-defined quantity in quantum field theory, and in the most general situations the theory cannot even define quanta (there is no Fock space representation). All this speaks against the idea that reality is particle-like in a fundamental sense.

The alternative to the Received View defended here accepts the conclusion that the particle concept is not fundamental. Even at the level of ordinary quantum mechanics (i.e., at the level where quantum field theory is not needed) particles must be seen as *emergent* entities: there are many situations adequately described by quantum mechanics that do not fit into a particle model. The notion of a particle only becomes useful in cases where one-particle wave functions manifest themselves individually, at least in good approximation (we will discuss some of the qualifications that must be made in section 5). In the case of fermions such one-particle wave functions are always orthogonal and therefore distinguishable. The particles that emerge in this way are thus characterised by a Leibnizian identity associated with their wave function.

If particles can emerge, they can also disappear again into a non-particle background; the life of an individual quantum particle may be very short. Since we assume that quantum theory is a fundamental theory, also valid at the macroscopic level, this caveat regarding the restricted validity of the concepts “particle” and “particle identity” must be made, in principle, even when discussing macroscopic physics. *All* particle identity is emergent and (in principle) ephemeral, so that the robust notion of a particle and its identity considered as fundamental in classical physics should be rejected. But as long as a particle picture is adequate, the particles involved do possess identity. According to the view we defend, distinguishability and identity are even prerequisites for the applicability of the particle concept.

3. Quantum statistics and identity

As mentioned in the introduction, an influential argument for the thesis that quantum particles do not have a Leibnizian identity stems from quantum statistics. In the statistical mechanics of classical particle systems Maxwell-Boltzmann statistics is standardly used, while systems of quantum particles of the same kind are assumed to follow either Bose-Einstein statistics (bosons) or Fermi-Dirac statistics (fermions). The essential difference between classical MB statistics and the two types of quantum statistics is that permuting two particles is considered to lead to a new physical state in the classical case, while permutations of quantum particles of the same kind leave the total state invariant. There are consequently more classical than quantum permutation variants of a given state.

Both standard classical and quantum statistics assign equal probabilities to all available states. Differences between classical and quantum probabilities therefore arise from differences in the number of available states (see the coin toss example in the Introduction for illustration). The applicability of the BE and FD probability distributions in the statistical-mechanical treatment of typical quantum phenomena has been very well confirmed experimentally, as has the applicability of MB statistics to classical systems. These facts are widely considered conclusive evidence that permutations of quantum particles of the same kind have no physical meaning, unlike permutations of classical particles. Classical particles thus appear to possess a physically relevant identity, while quantum particles do not.

To evaluate this argument, it is helpful to first consider the details of the classical case. Following Leibniz's principle, the identity of each of two classical electrons 1 and 2 must be understood as based on their individual physical properties: their different positions and different histories (which define their genidentity). As noted in the Introduction, permutation of these Leibnizian identities without a physical process is an inconsistent concept. After all, a classical electron whose identity consists of occupying position 1 and having a certain velocity at that position cannot possibly, even in thought, be in position 2. Of course, it is possible for electron 1 to be moved to position 2 or to move there on its own. But then it is still the same electron as before, previously in position 1, and no change of identity has occurred. It follows that, within the Leibnizian framework, which rejects haecceities and other non-empirical identity principles, it makes no sense to specify the positions of two classical electrons via the two-particle state at some time (a synchronic description), and then ask the question, "which particle is at position 1 and which is at position 2?" Nor does it make sense to specify two histories in a diachronic description and ask, "which particle follows which path?" The argument that a given classical *n*-particle configuration should be assigned a statistical weight of *n!* on the grounds that the particles can be interchanged is therefore invalid.

This is not a problem, however, because we do not need the concept of "identity exchange" at all to justify the applicability of MB statistics to classical particle systems. The fact that each particle has its own diachronic identity (genidentity), determined by its classical trajectory, proves sufficient to ground classical statistics.

To see this, suppose that two classical particles of the same kind, initially at different positions 1 and 2, are set in motion and can each end up in either spatial region T or spatial region H. Assume also that chaotic external influences, acting independently on each of the two particles, make this a probabilistic process with equal probabilities for the outcomes T and H. Then the outcomes TT, HH, and HT have probabilities of ¼, ¼, and ½, respectively. The probability of HT is twice as large as the probabilities of TT and HH, because in this case there are two possibilities: the particle originating from 1 ended up in T and the other particle in H, and vice versa. These are physically distinct processes due to the genidentity of classical particles. Consequently, there are twice as many realisations for HT as for TT and HH, and this will manifest itself in the long run in the relative frequencies with which these outcomes occur. That the outcome HT is twice as likely as the outcomes TT and HH is typical of Maxwell-Boltzmann statistics.

It is important to emphasise that the applicability of Maxwell-Boltzmann statistics cannot be understood by simply specifying all possible final states of the two particles. These would be the three states corresponding to HT, TT, and HH, and without further physical information about how these possibilities can be realized, it is impossible to say anything reliable about the probabilities with which these states will occur. Invoking the principle of insufficient reason would lead to the probability assignment ⅓, ⅓, ⅓, which directly contradicts Maxwell-Boltzmann. The suggestion that assigning haecceities, 1 and 2, to the particles would solve this problem, because in that case the outcome HT can be realized as H1T2 or H2T1, does not help. Haecceities (and similar non-physical principles) cannot, in principle, make any difference, since they play no role in the laws of nature. The presence or absence of haecceities can therefore in no way explain empirically observable differences.

The applicability of Maxwell-Boltzmann statistics must therefore be related to the existence of *physical* differences. As we have seen, the crucial point in the situation described above (or the fair coin toss) is the existence of distinct physical trajectories, each subject to independently fluctuating external forces. Particle identity certainly does play a crucial role in explaining the behaviour of classical particles, but it is the Leibnizian identity that is determined by positions and trajectories.

Let us now turn to the statistics of quantum particles. First, consider the case of bosons. Suppose we have two bosons and two available one-boson states, $|H\rangle$ and $|T\rangle$. Total boson states must be symmetric, so there are the following three possibilities: $|H\rangle|H\rangle$, $|T\rangle|T\rangle$ and $\frac{1}{\sqrt{2}}(|H\rangle|T\rangle + |T\rangle|H\rangle)$. At any given time (synchronously), there are thus three possible states; note that this is exactly the same as in the case of two classical particles of the same kind. Without further diachronic information about the way the situation can arise, it is impossible to make a reliable prediction about the probabilities or frequencies of occurrence of these states in repetitions of the situation. If we know that the three states are chosen at random, or that they have the same frequency because of ergodicity or some similar physical property of the evolution process, then all three of them can be assigned the same probability, namely ⅓. This is the typical probability assignment in Bose-Einstein statistics. The probability that both particles are in the same state, either $|H\rangle$ or $|T\rangle$, is then twice the probability that the particle are in different states. This BE probability differs significantly from what the MB distribution predicts, namely that it is equally likely that the two particles are in the same state as that they are in different states.

The prevailing view is that this difference is a direct consequence of the difference in available synchronous states, namely four in the classical case and three in the boson accident; and that this difference, in turn, is due to the fact that classical particles have an identity, while bosons do not. The suggestion, pervasive in the literature (French and Bigaj 2024, section 2), is that this difference in the number of available synchronous states alone provides compelling evidence that bosons do not have an identity. In this form, however, the reasoning is flawed. As we have seen, the number of available synchronous physical states in the classical two-particle case and in the boson case is exactly the same, namely three, if we reject haecceities and the like. Simply counting the number of states cannot, therefore, teach us anything about the difference between classical and quantum particles.

As we have seen, however, it is true that classical particles possess a diachronic identity, and that we can use this to supplement the synchronous state with labels, by having them refer to the initial positions from which the particles departed. If we assign equal probabilities to all types of histories, rather than to the three possible final states, we obtain the Maxwell-Boltzmann distribution. The argument for Maxwell-Boltzmann statistics based on the permutation of particle labels can thus be justified retrospectively by giving those labels physical substance.

This consideration sheds new light on the nature of quantum statistics. As we argued in section 2, in some cases even quantum particles can acquire genidentity, namely if individual wave functions are traceable in time. Suppose we start with two bosons characterised by wave functions localised in two well-separated regions, 1 and 2, respectively. Suppose further that we can track these two bosons for at least some time. Finally, let us assume that during this time the two one-boson wave functions each evolve into either the state $|H\rangle$ or the state $|T\rangle$, depending on how they are influenced by random potentials (analogous to the random forces in the classical case of tossing two coins). Throughout this process, the total two-particle state must be symmetric. Therefore, at the end of each experimental run there are only three possible two-boson states. Nevertheless, exactly the same considerations apply as in the classical case. That is, if equal probabilities are given to all types of single wave function evolutions, $1 \rightarrow H,\ 1 \rightarrow T,\ 2 \rightarrow H$, and $2 \rightarrow T$, the three possible final situations HH, TT and HT will occur with the probabilities corresponding to the Maxwell-Boltzmann probability distribution.

This is not to deny the importance of Bose-Einstein statistics for explaining many highly relevant quantum phenomena, such as Bose-Einstein condensation. The assumption that all possible synchronous states are equally likely is apparently justified in such cases, and this can be interpreted as reflecting a lack of Leibnizian single-particle genidentities in these phenomena, which are far removed from the classical regime. According to our alternative view, it would be more accurate to say that a single-particle picture is not applicable in these cases. However, as we have just shown, there are also cases where a single-particle picture *is* applicable, and in these cases, the assumption that all synchronous multi-boson states are equally likely is generally incorrect—in fact, Maxwell-Boltzmann statistics may be valid. Therefore, the argument against quantum particle identity based on quantum statistics is somewhat circular. The argument rests on an assumption about equal probabilities that is directly related to the conclusion to be drawn. As we saw, the usual assumption of equal probability for all possible final states is not automatically plausible if the quantum particles possess (approximately) a genidentity: the system might even perfectly mimic a classical particle system. In other words, the choice of the statistical premise underlying the argument is also a choice of the conclusion that can be drawn. As illustrated, there is no self-evident, unique, and generally valid choice, while the prevailing approach in the literature suggests otherwise.

Assigning probabilities to the occurrence of states always requires a detailed consideration of the physical context, including the way the states are produced. As another simple example, suppose we have a bosonic state of the following form: $|\Phi\rangle|\Phi\rangle$, with $|\Phi\rangle = \frac{1}{\sqrt{2}}(|H\rangle + |T\rangle)$. This state does not describe two separate bosons but, in our interpretation, a single entity (a mini Bose-Einstein condensate). If we measure the projection operators $|H\rangle\langle H|\otimes|H\rangle\langle H|$, $|T\rangle\langle T|\otimes|T\rangle\langle T|$ and $|H\rangle\langle H|\otimes|T\rangle\langle T| + |T\rangle\langle T|\otimes|H\rangle\langle H|$ in this state, there are three possible outcomes, corresponding to the symmetric post-measurement states $|H\rangle|H\rangle$, $|T\rangle|T\rangle$ and $\frac{1}{\sqrt{2}}(|H\rangle|T\rangle + |T\rangle|H\rangle)$. As can easily be seen from the form of the initial state, quantum mechanics predicts that the associated probabilities are: $p(HH) = p(TT) = 1/4$, $p(HT) = 1/2$. These are the probabilities associated with Maxwell-Boltzmann statistics and classical coin tossing, rather than what might be expected from Bose-Einstein statistics and the adage that bosons like to flock together,

For fermions, the situation is different: there is only one two-fermion state that can be constructed from the one-particle states $|H\rangle$ and $|T\rangle$, namely $|\Psi\rangle = \frac{1}{\sqrt{2}}(|H\rangle|T\rangle - |T\rangle|H\rangle)$. The quantum analogue of the coin toss experiment has in this case only one possible outcome, since the states $|H\rangle|H\rangle$ and $|T\rangle|T\rangle$ are impossible. This is similar to the classical principle of impenetrability, for which the quantum mechanical anti-symmetrisation prescription provides the explanation.

The situation changes, however, as soon as we assume the existence of more properties, which are able to make the particles physically different. Thus, we can obtain two electrons in states $|H\rangle|H\rangle$ and $|T\rangle|T\rangle$ if they differ in their spin properties: $\frac{1}{\sqrt{2}}(|H,+\rangle|H,-\rangle - |H,-\rangle|H,+\rangle) = \frac{1}{\sqrt{2}}|H\rangle|H\rangle(|+\rangle|-\rangle - |-\rangle|+\rangle)$, where $+$ and $-$ denote the different spin properties. This is an allowed anti-symmetric state. Electrons that differ from each other in terms of their spin can therefore produce the outcomes HH, TT and HT. In this case the same considerations apply as before. We can set up an experiment in which two electrons, one with spin "up" and one with spin "down", are initially located at different positions and are "tossed" independently of each other, with equal probabilities for the different possible types of histories. The result is Maxwell Boltzmann statistics, despite the quantum nature of the fermions.

4. Identity and mock identity

The alternative approach says that the particle concept is synchronously applicable insofar as distinguishable single-particle states manifest themselves at a given moment; if individually distinguishable wave functions remain distinguishable over time, this offers the possibility of assigning diachronic identities. Following particles over time is possible, for example, if there are no interactions between the particles. In this case, each individual wave function evolves independently and deterministically according to the free Schrödinger equation. In the Hilbert space representation, where states are represented by vectors, this corresponds to individual state vectors undergoing deterministically determined rotations. Orthogonal vectors, which represent perfectly distinguishable states, remain orthogonal under such evolutions.

If two particles of the same kind meet and interact, with overlapping wave functions, the outgoing wave functions may not be genidentically related to the incoming wave functions. For example, suppose that before the interaction there is one free-moving electron with wave function ψ, and one with wave function ϕ, and after the interaction there are again two free-moving electrons, now with respective wave functions μ and ν; then it may be that there is no answer to the question of whether the μ electron is the same as the ψ electron or the ϕ electron. This is not meant to be due to a lack of knowledge, but rather because the identities of the incoming particles did not survive the interaction: the two original electrons merged, while two new electrons were subsequently created. But it is not the case that such an identity loss *must* occur in interactions: if the original electrons had distinctive properties unaffected by the interaction, for example a spin value that distinguished them, then a genidentity relationship can persist between before and after the interaction (Bigaj 2020). Which of these possibilities applies, loss or preservation of identity, depends on the details of the case.

These considerations are of direct relevance to physical practice, in which it has become routine to isolate and manipulate elementary quantum particles. The Nobel Prizes in Physics for 1989 and 20012 were awarded for the development of techniques for creating and observing “individual quantum particles”, as the Nobel citation stated. The 1989 Nobel laureate Dehmelt became famous for holding a single positron in the same place for three months, naming it “Priscilla” and subjecting it to measurements. He could have continued the experiment for an arbitrarily long time. The ability to stably isolate quantum particles of the same kind is currently of great importance for the development of quantum computers, in which such particles can serve as elementary units (qubits). In these cases, our analysis fits physical practice very well.

However, from the standpoint of the Received View it cannot be correct to talk about individual particles of the same species possessing genidentity. According to the Received View it may at most be a pragmatic decision, useful for limited practical purposes, to pretend that particles with an identity exist; however, a fundamental analysis of the nature of physical reality is hindered rather than helped by such pragmatism. In this vein, Toraldo di Francia (1985) wrote: "an *engineer*, *discussing a drawing*, can temporarily make an exception to the anonymity principle and say for instance: ‘Electron *a* issued from point *S* will hit the screen at *P* while electron *b* issued from *T* hits it at Q’. But this *mock individuality* of the particles has very brief duration." (Emphasis added.) In a later publication (Dalla Chiara and Toraldo di Francia, 1993), the objection was modified---perhaps because of Dehmelt’s work in which isolated particles were tracked for months. In the new argument it was conceded that “mock identities” can exist for a long time and can have names associated with them; for instance, an electron might be called Peter and might be identifiable for hours. But according to Dalla Chiara and Toraldo di Francia, Peter nevertheless does not possess a *real* identity. Indeed, they argue, a real identity should be robust under all changes of context; it should persist in transitions to other possible worlds. They write (p. 267): “Suppose that we follow with continuity an electron---say Peter---going from point *P* to point *Q* in a vacuum. We would like to be able to say that in a possible world Peter might encounter other electrons on its path and finally be scattered to *Q*. But then no one could tell that that electron is still Peter. There is no *trans-world identity*.”

In a number of recent articles, Décio Krause (2024, 2025a, 2025b) has raised similar concerns, plus a number of other objections to our alternative view. In Krause (2025a) the following definition of an individual is given: something is an individual if “(i) it is a unity of a kind, say a table, a person, a pen; (ii) it has *genidentity*, that is, it can be re-identified *as such* individual in different contexts; we can say that it has *material genidentity* in the sense of Reichenbach. An alternative way is to say that individuals have *diachronic identities*, that is, we can say that individual 1 at time t_1 *is the same* (diachronically identical) as individual 2 at time t_2.” This definition matches the notion of identity that we claim for our view’s emergent particles, as long as they do not disappear.

The different contexts mentioned in Krause’s identity criterion are stipulated to be connected via diachronic identity; that means that these contexts are ordered in time, within one single world. This makes Krause’s identity definition different from the modal one employed by Toraldo di Francia, who required trans-world identity. Nevertheless, in other places in his articles (e.g., Krause 2025a, section 1), Krause states that the names of genuine individuals (as opposed to mock or fake individuals) can serve as rigid designators, so that he takes Toraldo’s modal aspects of identity on board as well. We will therefore briefly discuss arguments against the alternative view based on both types of objections: that emergent entities lack one-world genidentity and that they lack trans-world identity.

In his three papers (2024,2025a, 2025b), Décio Krause contrasts our emergent quantum particles with what he considers paradigmatic examples of real individuals, namely Caesar, Cleopatra and Pompey. He writes: “Julius Caesar was a man and *the same man* when in Rome and when in Egypt”, and “A core property of an individual is its re-identification: Cleopatra was an individual and she was *the same* woman either when in Egypt and when entering Rome”. I agree, this is in no way problematic. Genidentity is the crucial factor in these cases. From a physical point of view, this genidentity consists in the uninterrupted causal evolution of the persons mentioned, seen as physical systems. If, at some point during his journey, a double had covertly taken Caesar's place, the

Caesar welcomed in Rome would not have been the same man who left Egypt, even if the double was so perfect that no distinction could be made in Rome.

But what is the difference between these cases and the emergent quantum particles of the alternative approach, which, as we have explained, also possess individualising properties and genidentity---even though these emergent entities may only exist for a limited time? Take Dehmelt's Priscilla, which could be tracked in time for three months. If Dehmelt had wanted to, he could have moved Priscilla from Egypt to Rome during that time. In that case, the alternative approach would have concluded that the same Priscilla who left Egypt had arrived in Rome.

But this conclusion is rejected by Krause. He writes (Krause 2025b, p. 42): “But there is a huge difference between a quantum entity and Julius Caesar. Julius Caesar existed during a certain period of time and had its STI-identity [*identity according to the Standard Theory of Identity, which is also used in the alternative approach*], being able to be discerned from any other human being (let us keep with human beings only). Of course the situation would be different if instead of Julius Caesar being kidnapped by the pirates it was Pompey who was kidnapped by them. But when you trap a quantum object in your laboratory, it is indifferent which quantum object is being trapped, only its *kind* imports. Once out of the trap, or ‘dead’, the particle will never be remembered as *that* particle that was in the trap, but we shall just have a resemblance that *some* particle of a certain kind was there. Contrariwise, Julius Caesar also died, but we do not refer to that historical period as indicating that *some* Roman general lived there and made such and such things, but that it was *that* specific human being who did that. His STI-identity did not die with him; *his* fame continues until today.”

I assume that this passage is not intended to claim that Caesar's identity is determined by something that exists independently of Caesar's physical and mental properties, in combination with facts about Caesar's history. Indeed, in his writings, Krause explicitly emphasises that he rejects the use of haecceistic or similar non-empirical identity principles. But if that is the case, i.e. if the identity of both humans and physical objects is determined by the usual characteristics we attribute to them, it is unclear how the just-quoted passage can serve as a criticism of the alternative approach. As we have explained, the alternative view is precisely that an individual quantum particle emerges when individuating physical properties are instantiated, and this is exactly what happens in the case of Priscilla. The trapping procedure can be seen as the birth of Priscilla (represented by the “preparation” of the corresponding localised single particle wave function, as the physicist's jargon says). Priscilla is the unique positron in Dehmelt's trap, christened Priscilla by Dehmelt. We therefore still remember Priscilla as the positron in Dehmelt's laboratory, christened by Dehmelt, even though she no longer exists.

The objection that we cannot possibly know which positron was captured in the trap seems based on a misunderstanding. There are two possibilities: either the captured particle was created during the capture, or it had emerged earlier and was then captured. In the latter case, if particles already existed before the trapping process, the question of which particle was trapped is meaningful. In this case, however, there is no fundamental reason why we should not be able to know which of the pre-existing particles was trapped. On the other hand, if there were no pre-existing particles, then the question "which particle became Priscilla?" is misguided: Priscilla was *born* in the trap.

As already mentioned, Toraldo di Francia and Krause also contend that names like Priscilla cannot function as rigid designators, whereas genuine individuals have names that do. Therefore, they conclude, emergent particles (like Priscilla) cannot be individuals. However, I see no valid reasons for the premise that a name like Priscilla cannot function as a rigid designator.

Priscilla is the name Dehmelt gave to the particle he created in his trap. We can invoke a causal reference theory here, linking the name to a "first baptism." Our current use of the name Priscilla is linked to that first baptism via a causal chain, transmitted by the scientific community and scientific literature. The rigidity of the name Priscilla therefore does not seem to differ in essence from that of the name of a newborn baby. As such, it can be used to make counterfactual statements that are true in some possible worlds. For example, if Dehmelt had decided to terminate his experiment after a month, Priscilla would still have been there, but only for a month. If Peter, the electron introduced by Toraldo di Francia (see the above quotation), instead of continuing his journey undisturbed as in our world, is scattered, it depends on the details of the scattering interaction whether Peter survives that interaction. There may be other worlds in which Peter disappears during the scattering process, and worlds in which Peter hits *Q*. In any case, Peter remains himself as long as those changed circumstances have not occurred. If Dehmelt had conducted his experiment a day later, Priscilla would have been born a day later. And so on.

So I think that trans-world reference is possible for the names of emergent quantum particles. And don't forget that, according to our analysis, ordinary macroscopic things consist precisely of such emergent quantum particles – and we have no problem assigning an trans-world identity to ordinary macroscopic things.

In several earlier publications (Dieks and Lubberdink 2011, 2022; Dieks 2023a, 2023b, 2025b) I have used a simple example to illustrate the main idea of the alternative approach, namely a two-particle wave function that in bra-ket notation looks as follows: $\frac{1}{\sqrt{2}}(|L\rangle|R\rangle - |R\rangle|L\rangle)$, in which $|L\rangle$ and $|R\rangle$ are two mutually orthogonal quantum states corresponding to one-particle wave functions localized on the far left and far right, respectively. As explained earlier, the alternative view is that this represents two particles, one on the left and one on the right. These particles are characterised by the states $|L\rangle$ and $|R\rangle$, respectively. That is, the *identities* of these particles are *defined* by these two states (whether these identities are only synchronic or also diachronic depends of course on the evolution of the two-particle state; see also the next section for a discussion of qualifications that should be made). Krause (2025a) criticizes this core idea of the alternative approach, writing:

"Being in $|L\rangle$ or being in $|R\rangle$ do not provide *identity* to the particles. If we close our eyes for a moment and an evil genius appears and says that he *probably* has permuted the particles, how could we know whether he is telling the truth? Any measurement will give the same result independently of *which* particle is in the left (right), something that is typical of quantum physics. This is not compatible with the identity ascribed by STI; if someone says that in a football team, he has exchanged Lionel Messi for Cristiano Ronaldo, we all will notice the difference. But, in the case of quantum entities, we will never be able to know if the genius is telling the truth."

This criticism is based on a misinterpretation that also seems to underlie the Caesar-Cleopatra-Pompey objection mentioned above. The alternative approach does *not* say that two pre-existing entities have ended up in states $|L\rangle$ and $|R\rangle$, respectively, if the total state has the form $\frac{1}{\sqrt{2}}(|L\rangle|R\rangle - |R\rangle|L\rangle)$. Instead, the idea is that this state represents two particles that are *defined*, together with their Leibnizian identities, by the two distinguishable states $|L\rangle$ and $|R\rangle$ (or, equivalently, by the corresponding localised wave functions). According to quantum mechanics, one-particle *states* can be associated with one-particle *properties* and these properties can be used to define the particles via STI (more technically, the properties in question are represented by projection operators $|L\rangle\langle L|$ and $|R\rangle\langle R|$). It makes no sense to instantaneously permute a particle whose identity includes "being Left" with a particle whose identity includes "being Right", as discussed in the Introduction. As explained there, the same comment applies to classical mechanics, when haecceities and similar non-empirical identities are not allowed: it makes no sense to swap, in thought, the identities of two classical electrons. There is nothing typical of quantum mechanics here.

On the other hand, what does make sense (as also discussed in the Introduction) is to exchange the particles via a physical process. If the particles have genidentities in the way of Priscilla and Peter, this can be done via continuous causal paths. That is, by moving the emerged quantum particles, they can be exchanged, in the same way as Messi and Ronaldo. However, such physical exchanges are not undetectable, contrary to what is suggested in the above quotation. Why should we close our eyes as Krause asks us? When we keep them open, we could see the exchange (by shining light on the particles, or some similar technique). Again, there is nothing typical of quantum mechanics here. Indeed, suppose we have a truly perfect double of Messi---something that is of course impossible in practice, but not ruled out by physical law. Then no measurement on the football field could tell who is playing. But a video of what happened in the dressing room, where the coach possibly switched the two players, would end all uncertainty.

5. Approximations and decoherence

Emergence is not a question of all or nothing. Particles will emerge only gradually and under certain conditions. The use of particle descriptions will therefore often involve approximations and idealisations.

Suppose, for the sake of illustration, that we have an anti-symmetrized product of two one-particle states, $\frac{1}{\sqrt{2}}(|\psi\rangle|\phi\rangle - |\phi\rangle|\psi\rangle)$, with $|\psi\rangle$ and $|\phi\rangle$ two mutually orthogonal one-particle states. According to the alternative approach, in this case we are entitled to say that there are two distinct particles (with synchronic identities), with identities given by $|\psi\rangle$ and $|\phi\rangle$. Measurements that test for the presence of $|\psi\rangle$ and $|\phi\rangle$ particles will confirm this interpretation: measurements of the quantities $|\psi\rangle\langle\psi|$, $|\phi\rangle\langle\phi|$ and functions thereof will give exactly what can be expected from a situation in which one

$|\psi\rangle$ and one $|\phi\rangle$ particle is present. In particular, no results showing interference effects between $|\psi\rangle$ and $|\phi\rangle$ will be found in this type of measurements. But now suppose that we plan to measure a quantity of a different kind, namely one that does not perfectly distinguish between $|\psi\rangle$ and $|\phi\rangle$. For example, we might consider the joint probability of finding one particle at position x_1 and the other at position x_2, in a case where $|\psi\rangle$ and $|\phi\rangle$ correspond to wave functions that overlap in space. If we had two independent fully classical particles, we would expect that this probability equals the probability that the $|\psi\rangle$ particle is found at x_1 and the $|\phi\rangle$ particle at x_2, plus the probability that the $|\psi\rangle$ particle is found at x_2 and the $|\phi\rangle$ particle at x_1. However, quantum mechanics gives a different prediction, namely the classical probability we just described plus an "interference term". The formula reads: $p(x_1, x_2) = |\psi(x_1)|^2 . |\phi(x_2)|^2 + |\psi(x_2)|^2 . |\phi(x_1)|^2 - 2Re\{\psi(x_1)^* \phi(x_2)^* \psi(x_2) \phi(x_1)\}$, where the asterisk denotes complex conjugation and the third term is the interference term.

In this situation, there are certainly no two classically describable particles with well-defined positions. Nevertheless, for practical purposes, we may wish to model the situation, at least approximately, using a particle picture in which the particles can be distinguished from each other in space, as always can be done in classical mechanics. It is clear that this is only possible without falling into inconsistencies if the interference term is small enough to be neglected. What exactly "small enough" means depends on the use we want to make of the classical representation. But even if such pragmatic conditions are met, we are still dealing with an approximation: in principle, it remains possible to empirically refute the exact validity of the classical particle picture.

Suppose a position measurement is performed, and particles are found at x_1 and x_2, respectively---or, more realistically, in small spatial regions around these two points. As a result of this measurement, the state describing the overall system changes. We do not wish to go into the controversies surrounding the description of quantum measurements here (this would lead into the "quantum measurement problem"), and we will use the collapse of the wave function (projection postulate); this is the generally accepted description at least of what *effectively* happens to the state from the perspective of the observer[2].

Then the following transition takes place as a result of the measurement: $\frac{1}{\sqrt{2}}(|\psi\rangle|\phi\rangle - |\phi\rangle|\psi\rangle) \longrightarrow \frac{1}{\sqrt{2}}(|x_1\rangle|x_2\rangle - |x_2\rangle|x_1\rangle)$, so that after the measurement there are two spatially distinct particles localised at x_1 and x_2, respectively. If the original wave functions overlapped, this may be an example of a case where the identity of the original particles is lost due to interaction with other physical systems (here, the measuring device). Whether the post-measurement particles will have genidentity, i.e. whether they will follow more or less continuous paths, depends on the physical conditions. The localised one-particle wave functions created by the measurement interaction will tend to spread out, meaning that the particles will not automatically remain localised. This dispersion of the wave function can be counteracted by rapidly repeated position measurements. When this happens, the wave functions do not have enough time to

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[2] Actually, we prefer the treatment of measurements by unitary evolution, combined with a perspectival interpretation of the total wave function (Dieks 2022,2025a).

expand noticeably, making it possible to describe the situation with a localised particle model, as a good approximation.

It is an important physical fact that human observers and measuring equipment are not necessary to achieve such successive position determinations: natural processes can do this work. This is the essence of "decoherence", the process that makes the existence of the classical limit understandable. Under normal circumstances, the macroscopic environment around us interacts with quantum particles in a way that is comparable to almost continuous position measurements. This explains why we can often rely on a semi-classical particle picture, in which particles are entities that remain localised for a long time. Nevertheless, experiments over the past decades have shown that it is possible to create laboratory conditions in which decoherence is suspended. Under such conditions, even particles that we usually consider to be completely classical (e.g. very large molecules) may require description by means of wave functions that are not localised and exhibit interference effects in measurements.

Measurements, and more generally interactions with the environment, therefore play a role in determining the properties exhibited by particles. If the interactions we know were not local, i.e. comparable to position measurements, the fact that objects as we usually experience them can be treated as localised would be inexplicable.

But even if decoherence is at work, localisation is not entirely accurate. Highly sophisticated experiments can show that the classical description is only approximately correct, even though this approximation is extremely good under everyday conditions. And as already mentioned, conditions can be created in the laboratory in which decoherence is suppressed, so that even the quantum nature of ordinary objects become visible. We should therefore not think that the particle concept we extrapolate from our everyday experience, and the concept of identity associated with it, have exact validity in the physical world.

6. Conclusions

Fundamental physical theory shows us that the concept of a particle is not suitable for a description of the physical world that applies at all levels of reality. However, physics also teaches us that in domains where certain physical conditions are met, patterns in physical phenomena emerge that suggest particle behaviour---patterns that call to mind aspects of the behaviour of classical objects. In those domains, we can describe physical processes in terms of the interactions of individual entities, represented by single-particle wave functions---at least approximately. The closer we get to the classical regime, the better such particle models fit the phenomena and the closer they come to the models used by classical mechanics. Particles are therefore emergent entities.

Once they have emerged, quantum particles can be distinguished from each other and have an identity, even in domains that are relatively far removed from the classical domain. According to the view defended here, distinguishability is even an essential part of the criteria for assessing whether the particle concept can be applied at all. For the notion of particle to make sense, putative particles must be physically distinguishable and it must be possible to follow them for at least some time. This corresponds to the meaning of "particle" in macroscopic physics, from which the motivation for using the concept arises. In situations where no empirical distinction can be made between alleged particles, there is no physical justification for introducing the particle concept.

By contrast, the so-called Received View asserts that there are two types of particle, classical and quantum. Classical particles have an identity, quantum particles do not. We have examined the arguments for this position and the criticism of our alternative position and found them to be insufficient. In particular, we have argued that the widespread argument that the (anti-)symmetry of identical particle wave functions and the associated non-classical statistics (Bose-Einstein and Fermi-Dirac) directly demonstrate a lack of particle identity in the quantum realm is not convincing.

The view that particles are emergent invites the question of what the nature of reality is at the fundamental level where we can no longer speak of particles or objects at all. In certain domains, the field concept may offer a solution. In its full generality, however, the question concerns the ontology of fundamental quantum physics and beyond. This is a very important philosophical and physical question, which is unfortunately too extensive to cover in this article.

References

Bigaj, T. (2020). Synchronic and diachronic identity for elementary particles. *European Journal for Philosophy of Science* **10**, 33. Doi: 10.1007/s13194-020-00298-6.

Bigaj, T. (2022). *Identity and indiscernibility in quantum mechanics. New directions in the philosophy of science*. Palgrave Macmillan.

Caulton, A. (2014). Qualitative individuation in permutation-invariant quantum mechanics. arXiv: 1409.0247v1.

Dalla Chiara, M. L. and Toraldo di Francia, G. (1993). Individuals, kinds and names in physics. In G. Corsi, M. L. Dalla Chiara and G. C. Ghirardi (Eds.), *Bridging the gap: Philosophy, mathematics, and physics.* Boston studies in the philosophy of science, Vol. 140, pp. 261–284. Kluwer Academic Publishers.

Dieks, D. (2022). Perspectival quantum realism. *Foundations of Physics* **52**, 95. Doi: 10.1007/s10701-022-00611-8.

Dieks, D. (2023a}, Emergence and identity of quantum particles, *Philosophical Transactions of the Royal Society A* **381** (2255): 20220107.

Dieks, D. (2023b). Quantum individuality. In J. R. B. Arenhart and R. W. Arroyo (Eds.), *Non-reflexive logics, non-individuals, and the philosophy of quantum mechanics: Essays in honor of the philosophy of Décio Krause.* Synthese Library, Vol. 476, Chapter 2. Springer.

Dieks, D. (2025a). Radical perspectivalism, Locality and Relativity. *Foundations of Physics* **55**, 30. Doi: 10.1007/s10701-025-00844-3.

Dieks, D. (2025b). Identical particles in quantum mechanics: Against the received view. In D. Krause and J.R.B. Arenhart (Eds.), *Individuals and non-individuals in quantum theory.* Synthese Library, Vol. 525, Chapter 15. Springer.

Dieks, D. and Lubberdink, A. (2011). How classical particles emerge from the quantum world. *Foundations of Physics* **41**, 1051–1064.

Dieks, D. and Lubberdink, A. (2022). Identical quantum particles as distinguishable objects. *Journal for General Philosophy of Science* **53**, 259–274.

French, S. and Bigaj, T. (2024). Identity and individuality in quantum theory. In E.N. Zalta and U. Nodelman (Eds.), The Stanford encyclopedia of philosophy. Metaphysics Research Lab, Stanford University. https://plato.stanford.edu/archives/spr2024/entries/qt-idind/, Spring 2024 edition.

French, S. and Krause, D. (2006). *Identity in physics: A historical, philosophical, and formal analysis*. Oxford University Press.

Friebe, C. (2014}. Individuality, distinguishability, and (non-)entanglement: A defense of Leibniz's principle. *Studies in History and Philosophy of Modern Physics* **48**, 89–98.

Ghirardi, G., Marinatto, L., and Weber, T. (2002). Entanglement and properties of composite quantum systems: A conceptual and mathematical analysis. *Journal of Statistical Physics* **108**, 49–122.

Krause, D. (2024). On Dieks against the Received View. *PhilSci-Archive*, University of Pittsburgh. http://philsci-archive.pitt.edu/perl/search

Krause, D. (2025a). On the Received View versus the Alternative View controversy about quantum (non)individuality. *Foundations of Science*.Doi:10.1007/s10699-025-09974-3.

Krause, D. (2025b). On the controversy Received View vs. Alternative View. In D. Krause and J.R.B. Arenhart (Eds.), *Individuals and non-individuals in quantum theory.* Synthese Library, Vol. 525, Chapter 3. Springer.

Toraldo di Francia, G. (1998). A world of physical objects? In E. Castellani (Ed.), *Interpreting bodies: Classical and quantum objects in modern physic,* pp. 21–29. Princeton University Press.