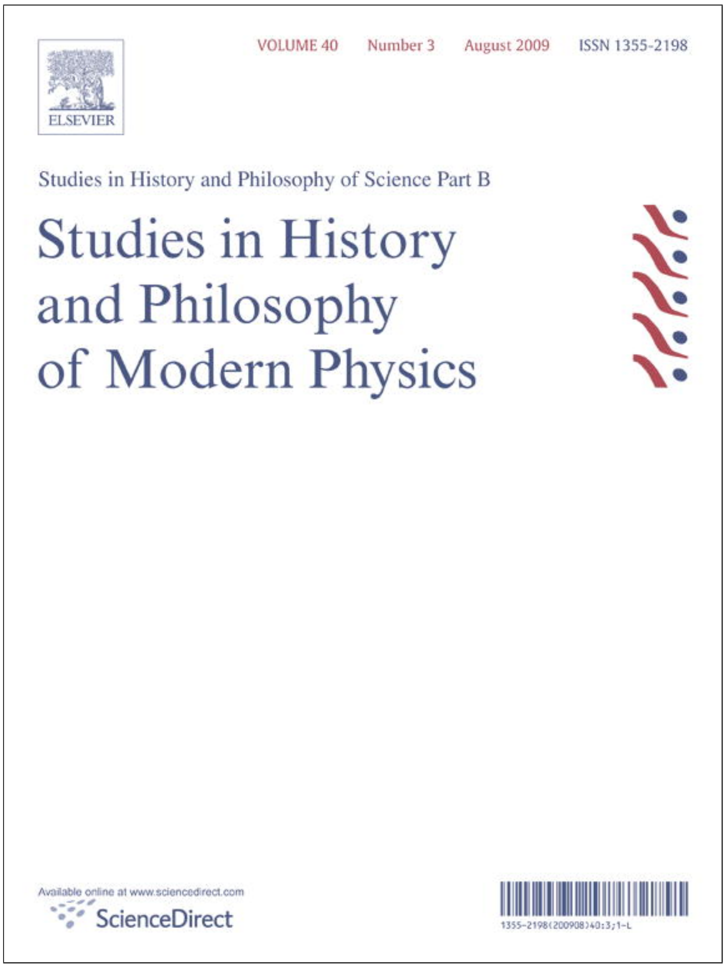

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Inherent properties and statistics with individual particles in quantum mechanics

Matteo Morganti

FB Philosophie and Zukunftskolleg, University of Konstanz, Universitätsstraße 10, 78464 Konstanz, Germany

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ABSTRACT

This paper puts forward the hypothesis that the distinctive features of quantum statistics are exclusively determined by the nature of the properties it describes. In particular, all statistically relevant properties of identical quantum particles in many-particle systems are conjectured to be irreducible, 'inherent' properties only belonging to the whole system. This allows one to explain quantum statistics without endorsing the 'Received View' that particles are non-individuals, or postulating that quantum systems obey peculiar probability distributions, or assuming that there are primitive restrictions on the range of states accessible to such systems. With this, the need for an unambiguously metaphysical explanation of certain physical facts is acknowledged and satisfied.

0. Introduction

The claim that since quantum particles obey a non-classical statistics they should be regarded as non-individuals, that is, as entities lacking well-defined identities, can be found as early as (Born, 1926). That quantum particles form aggregates of entities that are only ordinally countable, and of which it makes no sense to ask 'which one is which', has then become something like a 'Received View' on the matter (this claim is put forward, for instance, in French & Krause, 2006, Chapter 3). However, there have been attempts to show that the individuality of particles (be it primitive or determined in agreement with some form of the Leibnizian principle of the Identity of the Indiscernibles) should not be sacrificed given the evidence related to quantum statistics. As will be argued in what follows, though, these attempts are not entirely convincing. The present paper attempts to resist the Received View in a novel way. In particular, it will be maintained that, *whatever one's conception of individuality is*, a ready explanation of quantum statistics can be formulated by making a plausible assumption concerning the nature of the properties relevant for the statistics, essentially amounting to a generalization of some ideas expressed by Teller in the late 1980s. Section 1 gives an outline of classical and quantum statistics, explaining why the latter is commonly taken to force us to assume the non-individuality of quantum particles. Section 2 considers some existing attempts to block this inference and points out their limitations. Section 3 puts forward an alternative proposal, based on a form of 'ontological revision': namely, on the idea that all statistically relevant properties of many-particle systems of identical quantum particles are 'inherent' properties only belonging to the system as a whole. Section 4 adds some remarks and specifications, considering some potential objections and worries. A concluding section follows.

E-mail address: Matteo.Morganti@uni-konstanz.de
URL: http://www.uni-konstanz.de/zukunftskolleg/

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1. Classical and quantum statistics

Suppose one has N particles distributed over M possible single-particle microstates, and is interested in knowing the number of physically possible combinations.

In classical mechanics, Maxwell–Boltzmann statistics holds. According to it, the number of possible distributions W is

$$W = MN \tag{MB}$$

In the case of quantum particles, fewer arrangements are available. Bose–Einstein statistics (which applies to the particles known as bosons) has it that

$$W = (N + M - 1)!N!(M - 1)! \tag{BE}$$

In the case of fermions, the Exclusion Principle (dictating that no two fermions can be in the same state) holds and further reduces the number of possible states, which becomes equal to

$$W = M!/N!(M - N)! \tag{FD}$$

The latter expresses so-called Fermi–Dirac statistics.[1]

Consider now a physical system composed of two entities to each one of which two equally probable states are available (i.e., for which $M = N = 2$). Classically, one applies (MB) and obtains $2^2 = 4$ possible arrangements, each one with probability $\frac{1}{4}$ of being realised (think, for instance, of a system composed of two fair coins and the possible distributions of 'heads' and 'tails'). According to quantum statistics, instead, there are only either $(2+2-1)!/2!(2-1)! = 3$ possibilities (BE) or $2!/2!(2-2)! = 1$ possibility (FD) for systems of this type. The probabilities of occurring for each possible configuration are 1/3 and 1, respectively.

In more detail, the arrangements available in the situation being considered are the following (x and y being the available states, and the subscripts denoting the entities composing the system):

$$|x>_1|x>_2 \tag{C1 − Q1}$$

$$|y>_1|y>_2 \tag{C2 − Q2}$$

$$|x>_1|y>_2 \tag{C3}$$

$$|y>_1|x>_2 \tag{C4}$$

$$1/\sqrt{2}(|x>_1|y>_2 + |y>_1|x>_2) \tag{Q3}$$

$$1/\sqrt{2}(|x>_1|y>_2 - |y>_1|x>_2) \tag{Q4}$$

(C1)–(C4) are possible particle arrangements in classical mechanics, (Q1)–(Q4) the configurations available in quantum mechanics. In particular, (Q1)–(Q3) are symmetric states, accessible to bosons, while (Q4) the unique possible state for fermions, which is anti-symmetric.[2] (Importantly, the two kinds of quantum particles necessarily conserve their symmetry-type, i.e., there are no transitions from a fermionic to a bosonic state or vice versa.)

Comparing the classical possibilities and their quantum counterparts, it can immediately be noticed that in the quantum case *particle exchanges do not make a difference*. This is the case, it is generally agreed, not (only) because we could not tell which particle is which, but because ontologically there is only one way in which each macrostate can be realised. This is known as Permutation Symmetry, or Indistinguishability Postulate (quantum identical particles in the same system are consequently said to be indistinguishable). Moreover, non-symmetric states do not occur in the quantum case—that is, analogues of (C3) and (C4) for quantum particles are never realised. All this appears problematic for those who want to defend the individuality of particles. Consider the impossibility of non-symmetric states: if particles truly are individuals, why are states that would differ from allowed ones ((Q1) and (Q2) above) only as regards which value is exhibited by which particle not observed?[3]

The available evidence, the canonical argument underpinning the Received View goes, suffices for concluding in favor of the non-individuality of quantum particles. First, it is maintained, particle permutations cannot in principle make a difference in the quantum case because there are no identities that can be permuted. Secondly, and relatedly, non-symmetric states are not observed in the quantum domain because there it is impossible for *a specific* particle to have a certain value for an observable and for *another specific* one to have a different value for that observable, as the particles do not have determinate identities allowing for such property-attributions.

2. Attempts to avoid the conclusion

Those not willing to subscribe to the Received View on quantum statistics must provide an alternative explanation of the evidence. Alternatively, they will have to deny that physics, at least as far as the case under scrutiny is concerned, should be given a metaphysical interpretation. In this section, the three main existing attempts to explain quantum statistics without invoking non-individuality will be illustrated: one assumes indistinguishability and focuses on probability measures; one questions the equiprobability of the available states; and one postulates primitive state-accessibility restrictions. Then, a 'no metaphysics from the physics' reaction will be considered. Shortcomings in all four approaches will be pointed out. A more promising alternative will be presented in the next section.

2.1. Indistinguishability and probability measures

One argument against the conclusion that quantum particles must be considered non-individuals in view of their statistical behavior relies on a particular stance that it is possible to take with respect to the so-called 'Gibbs paradox'. The Gibbs paradox consists of the fact that (MB) incorrectly predicts that by mixing similar gases at the same pressure and temperature one experiences a change in entropy, and this requires the introduction of a $N!$ factor excluding permutations in order to make entropy correctly extensive.

One suggested reaction to this is that in at least some cases classical particles are indistinguishable too, and this explains the need to employ the 'correct Boltzmann counting' to overcome Gibbs' paradox. Saunders (2006) expands on this in some detail, exploiting the resulting picture for an explanation of quantum statistics.

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[1] This tri-partition of types of statistics on the basis of types of particles may be disputed, for example by claiming that classical systems obeying Bose-Einstein statistics are both theoretically and, it seems, practically possible (see, for instance, Gottesman, 2007). However, it looks as though a general distinction can in fact be drawn meaningfully on the basis of what is the case under normal circumstances.

[2] (Q3) and (Q4) describe the *entangled* states typical of quantum mechanics, for which it is true that the component particles have identical probabilities for measurement outcomes, but it is also certain that these outcomes will be one the opposite of the other.

[3] As will be seen in what follows, the seeming awkwardness of this question rests on the tacit assumption that in all the statistically relevant states *there always is* a property possessed by each particle as *its* property.

Saunders rejects both the claim that classical indistinguishability is incoherent (Bach, 1997; Van Kampen, 1984) and that it is unnecessary (Ehrenfest & Trkal, 1920; Van Kampen, 1984), and contends that

> indistinguishability (permutability, invariance under permutations) makes just as much sense classically as it does in quantum mechanics (Saunders, 2006, p. 200)

and indeed we should infer from the evidence that both classical and quantum particles are statistically indistinguishable.

On the basis of this assumption of indistinguishability, Saunders provides his explanation for the statistics. The difference between classical and quantum statistics, he contends (Saunders, 2006, p. 203), is due to the breakdown, as $C_k \gg N_k$, of the approximation

$$\frac{(N_k + C_k - 1)!}{N_k!(C_k - 1)!} \approx \frac{C_k^{N_k}}{N_k!} \tag{1}$$

(with C_k denoting the number of cells in the kth frequency range, and N_k the particles that lie in region k). Such a breakdown is, in turn, entirely determined by the fact that the equilibrium measure is continuous in classical phase space, and discrete in Hilbert space. This is to say, roughly put, that while every point in configuration space is equally available to classical particles, quantum particles only occupy specific 'areas', and tend to 'group together' in ways directly mirrored by the statistics.

Saunders' suggestion is, then, that in order to account for the difference between classical and quantum statistics, a *tu quoque* argument in favor of classical indistinguishability (which finds support in Gibbs' paradox) just needs to be supplemented by a consideration about probability measures that does not entail anything concerning particle identities. It follows that the Saunders line of reasoning constitutes an alternative to the Received View.

There are at least two difficulties with this sort of argument. First, the assumption of classical statistical indistinguishability is not uncontroversial.[4] Secondly, an *ontological* account of the nature and behavior of what is being described, going beyond a mere claim that there is a difference in probability measures, may still be legitimately demanded. Why are the probability measures different in the classical and quantum case? Why, more importantly, are only (anti-)symmetric, permutation-invariant states allowed for quantum systems?

2.2. *Equiprobability and the fundamental postulate of statistical mechanics*

While Saunders' explanation of quantum statistics rests on the assumption that all particles, classical and quantum, are indistinguishable, the reverse possibility was explored by Belousek's (2000), aiming to undermine the very assumption of quantum indistinguishability.

Belousek argues that whether quantum systems truly are permutation invariant depends on whether it is correct to assume the Fundamental Postulate of Statistical Mechanics (FPSM)—according to which every distinct equilibrium configuration must be assigned the same statistical weight—in the framework of quantum mechanics. Such an assumption, Belousek claims, is by no means inescapable. In actual fact, he argues, quantum particles can legitimately be regarded as distinguishable and, consequently, as individuals.

As shown by Tersoff and Bayer (1983), one can derive quantum statistics under a hypothesis of uniformly random a priori distribution of statistical weights over all possible microstates of the system, including states only differing by permutations. Just by assuming, in agreement with the basic axioms of probability, that each state is given a probability between 0 and 1, and that the sum over the probabilities for all states is 1, Tersoff and Bayer show that the observed statistical distributions correspond to the average over these random probabilities. Therefore, while given FPSM an assumption of distinguishability accounts for (MB) statistics and one of indistinguishability for quantum statistics, it is possible to obtain (BE) and (FD) statistics for distinguishable quantum particles by denying FPSM and postulating a random a priori distribution instead. In particular, if one gives up FPSM one can claim that the same number of states is in fact available to classical and quantum many-particle systems (although, obviously enough, with different probabilities).

FPSM is generally taken to hold because, in absence of any specific information about the system, it seems natural to think that it could be in any of the available states with the same probability. FPSM is therefore rooted in the Principle of Indifference. However, Belousek points out, the latter is itself object of philosophical debate, and far from obviously compelling. As a matter of fact, an assumption of random a priori probabilities may legitimately be regarded as logically weaker than one of equal a priori probabilities. Consequently, there is room for abandoning FPSM and claiming that quantum particles are distinguishable individual objects.[5]

This line of argument has the advantage, compared to the alternative exemplified by Saunders, that it grounds the defense of particle individuality on the well-understood concept of distinguishability. For this reason, it may *prima facie* appear quite appealing. Unfortunately, however, there are problems concerning both the explanatory efficacy of the proposal and its general plausibility.

First, even if one accepts that (although this fact is 'masked' by randomness in the distribution of probabilities) particle exchanges do in fact give rise to new macrostates in the quantum domain, the problem that non-symmetric states are never observed remains. Moreover, as Teller and Redhead (2000) point out, once some information about the physical system being described is available interference terms arise that make uniform priors necessary. An alternative theory based on non-uniform priors, they argue following Van Fraassen (1991, esp. pp. 417–418), has not been shown to exist, and appears indeed difficult to develop. For, since the assumption of distinguishability basically amounts to the positing of definite pre-measurement values for the individual particles, such a theory would seem to be in direct conflict with Bell-type no-go theorems.

2.3. *State-accessibility restrictions*

Some authors (see, for the first explicit statements of the view, French, 1989; French & Redhead, 1988) suggest that in order to defend the individuality of quantum particles it is sufficient to postulate certain primitive and non-further-explicable state-accessibility restrictions. Systems of indistinguishable particles, on this construal, are never found in non-symmetric states just because this is a fundamental feature of the world, in the same way as, say, the existence of quantum entangled states or the fact

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[4] The (dis-)solution of Gibbs' paradox might be interpreted—contrary to what Saunders suggests—as suggesting the need to switch from classical mechanics *as traditionally understood* to the non-classical ontological setting of quantum mechanics.

[5] In general, Belousek claims, quantum indistinguishability is conventional in the sense that it depends on a subjective choice between observationally equivalent hypotheses. For present purposes, however, Belousek's conventionalist conclusion can be ignored.

that fermions obey the Exclusion Principle. Indeed, if the initial condition is imposed that the state is either symmetric or anti-symmetric and there are no transitions from a state of one kind to a state of the other kind, then only one of two possibilities ((BE) or (FD) statistics) is open to any quantum system. In particular, if symmetrisation is a boundary condition, permutation symmetry is necessary to guarantee symmetry conservation. Consequently, the fact that ‘one particle in each state’ arrangements have half the probability in the quantum domain that they have classically is explained: it is just due to the fact that only symmetric (respectively, anti-symmetric) entangled states are ever available to bosons (respectively, fermions).

The crucial question is, of course, whether the conjectured restrictions on what is possible and/or on what is true at the level of initial conditions can be accepted as such. Some, like Huggett (1995), maintain that it is explanatory enough to claim that non-symmetric states are simply not in the symmetrised Hilbert space that correctly represents the actual world. One may object, however, that this line of reasoning refuses to seek explanations in cases in which it is legitimate to ask for them. Using the analogy provided by Teller (1998), for example, the view of quantum particles as individuals is unable to say *why* the world is described by a symmetrised Hilbert space, while statistical mechanics can explain, or at least attempt to explain, why a state of affairs in which a cold cup of tea spontaneously starts to boil is never observed. In view of this, one may argue, the interpretation of quantum statistics based on the Received View should be accepted in virtue of the fact that it is more explanatory (not doing so would be analogous to just taking facts of thermodynamics as primitive).

Furthermore, Redhead and Teller (1991, 1992) argue that there is the additional difficulty that non-symmetric states in quantum mechanics appear to be in principle useless (in Redhead’s (1975) terminology) *surplus structure*. Redhead and Teller suggest that, in view of the presence of such surplus structure, the use of the Fock space formalism of quantum field theory is to be preferred as—unlike the Hilbert space formalism—it does not make use of particle ‘labels’ and simply *cannot* describe non-symmetric state. The use of Fock spaces, however, (claim Redhead and Teller) appears to invite us to dispense not only with the labels, but with what they express at the ontological level too: namely, particle identities.

It could be countered, following French and Krause (2006, pp. 193–197), that Redhead and Teller’s argument is not compelling because there is a tension between the undeniable heuristic role of surplus structure in physics and the use of it as a basis for setting negative constraints on one’s ontological beliefs. Also, one might want to deny that the use of the Fock space formalism has any ontological significance, as the latter formalism meshes as well with an ontology of individual particles as with one of fields with non-individual ‘excitations’. More strongly, it has been argued that it is a theorem of Zermelo–Fraenkel set theory that labels can be unambiguously assigned to each one of a group of countable objects, and so French and Teller’s argument is formally mistaken (see Muller & Saunder, 2008, p. 526).

In any event, it remains a fact that non-symmetric states are not observed in quantum mechanics, while they are observed classically. And that the postulation of primitive restrictions and constraints on the evolution of physical systems as an explanation of this fact does not seem satisfactory, and could in fact considered rather *ad hoc*.

2.4. No metaphysics from physics?

A completely different reaction to the allegedly problematic evidence under discussion is presented by Huggett in a series of works (1995, 1997, 1999). Huggett argues that the idea that particle permutations should make a difference if particles were individuals depends on a supposition as to the truth of haecceitism: namely, the metaphysical doctrine according to which possible worlds can differ *de re* without differing qualitatively. That is, differ exclusively with respect to which object is which and/or which object possesses which property.[6] However, says Huggett, haecceitism is by no means necessary for individuality. In classical statistical mechanics, he contends, once realistic physical systems are taken into consideration it is equally possible to adopt a representation in terms of ‘distribution space’ (i.e., a description of what properties are instantiated where) and of ‘phase space’ (i.e., the canonical description in terms of individuals with properties). However, only the latter is wedded to haecceitism. Since, in any event, we do not put into question the metaphysical status of classical particles as individuals, it follows that no metaphysical consequences should be drawn from our theories, and in particular from the abstract space one decides to work in. This leads Huggett to maintain that quantum particles should not be regarded as non-individuals because of their indistinguishability: their metaphysical status is, instead, best regarded as underdetermined by the physics.[7]

It might seem that Huggett’s attempt to break the very connection between physical theory and metaphysics could be exploited by the supporters of the individuality of quantum particles. To do so, they would just need to isolate what Huggett says about individuality and haecceitism from his more general skepticism about the metaphysical import of physics, and use it in their own framework. In other words, if individuality is the ‘default position’, then the claim that the statistics does not have metaphysical import may suffice for sticking to the view that particles are individual objects without the need to provide any explanation of the evidence related to quantum statistics.

Teller (2001) and Gordon (2002), though, correctly point out that the evidence mentioned by Huggett bears witness only to the fact that more ‘incomplete’ descriptions are sufficient in the classical domain; and that it is far from clear that Huggett’s claims about the ‘metaphysical neutrality’ of physical theory are straightforwardly extendable to quantum mechanical systems. In particular, it is not at all clear that the two descriptions of many-particle systems (with and without haecceitistic differences) are available in the quantum domain. As we have seen, the only existing proposal for making permutations of particles without a qualitative effect on the macrostate count statistically in the quantum case—that is, the Tersoff–Bayer/Belousek proposal-faces undeniable difficulties.

It is therefore legitimate to think that Huggett’s ‘metaphysical agnosticism’ is not particularly convincing, at least as far as the quantum domain is concerned. And that quantum statistics does in fact require an explanation, and if one does not want it to be based on non-individuality, one should not be too satisfied with the present situation.

3. A new suggestion

It seems that those who intend to defend the position according to which quantum particles are individuals from the threat represented by quantum statistics must make a precise metaphysical claim about the particles themselves. Such a claim must account both for the particles’ ‘tendency to group together’ in permutation-symmetric arrangements and for the impossibility

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[6] And, it would also seem, at least if properties are not universals, which property-instance is which.

[7] Notice the contrast between Huggett’s ‘neutrality’ and Saunders’ positive claim that both classical and quantum particles are indistinguishable.

of non-symmetric states (and, therefore, for the irrelevance of haecceitism).

In the rest of the paper, it will be argued that this can be done by giving up an assumption that has been tacitly presupposed so far but is not, despite appearances, indispensable: namely, that everything qualitative *about* a particle must be encoded in a property that *it* possesses as *its* property. The claim will be put forward that in quantum many-particle systems of identical particles state-dependent properties are always properties that *belong exclusively to the whole system*. That is, that quantum statistics describes properties that have nothing to do with the identities of the components of the whole, as they are 'inherent' properties of the whole itself. This means, it will be argued, that the states described by the statistics are indeed insensitive to permutations, but this does not point to the fact that in actuality there are no permuted elements as particles lack definite identities. By the same token, the (anti-)symmetry of the relevant states is explained by denying that those states describe anything more than a disposition *of the system* to give rise to certain correlated outcomes upon measurement.

The rest of the paper will thus be devoted to providing the reader with two things:

(i) A definition of the view of properties being put forward, with reference to the proposal closest to it that can be found in the philosophical literature about quantum mechanics: Paul Teller's 'relational holism'.
(ii) A precise account of quantum statistics on the basis of the ontological perspective so defined.

3.1. *Holism, inherence and identity*

It is commonly claimed that quantum entanglement is a form of holism, the latter consisting, to use the typical slogan, of the fact that 'the whole is more than the sum of the parts'.

Teller (1986, 1989), in particular, designates as *particularism* the view that the world is composed of individuals possessing non-relational properties, and relations among which are 'reducible' to their non-relational properties. Reducibility is intended here in the sense that relations are nothing over and above (a subset of) the non-relational properties of their relata taken together: for example, the holding of the relation 'is taller than' between Alice and Bob *just is* the fact that Alice has a specific height (different from Bob's) plus the fact that Bob has a specific height (different from Alice's). Teller claims that the differences between classical and quantum mechanics are due to the fact that particularism is true of the entities dealt with at the level of the former, but not of those described by the latter. In the quantum domain, Teller argues, one must endorse *relational holism*: that is, the view that certain properties of the total system are irreducible relations that are not equal to a 'sum' of properties of the system's component parts. Teller calls these relations '*inherent*'. In particular, Teller considers as a reason to embrace relational holism the failure of factorizability for entangled states[8] and the related, experimentally confirmed violations of Bell's inequalities (Teller, 1989, esp. pp. 214–215).

Teller's perspective is the starting point for the rest of the present article. The idea that will be put forward is, in effect, little more than an 'extension', or 'generalisation', of relational holism: it is the idea that *the holistic view based on the notion of inherence must be extended to non-entangled systems*. That is, from states like (Q3) and (Q4) above, already dealt with in holistic terms by Teller (and others), to (Q1) and (Q2), a holistic understanding of which, it is contended, provides a solution to the puzzles raised by quantum statistics.

Of course, only in entangled states is the overall state non-factorizable in terms of separate states of the components. But non-factorizability is not a necessary condition for holism. And indeed, once holism has been acknowledged to hold for some quantum systems, one seems justified in accepting it also for other quantum systems insofar as doing so solves existing conceptual problems.

Before moving on, one significant remark needs to be made, and a bit more about the type of properties assumed to play the key role must be said.

Quite importantly, the 'relational' label will be dropped in what follows, as it is not essential for present purposes. The claim will be that in all many-particle systems of identical quantum particles, the state-dependent properties of the particles 'merge' into an inherent, holistic property of the whole. As will be illustrated shortly, the fact that the latter conveys information about the components of the whole need not be interpreted as entailing that such property is a relation. Hence, holism will be endorsed, and it will be left open whether it is relational or otherwise, in what follows.[9]

As for the notion of an inherent property, it will be taken to be a property *P* with the following characteristics:

(i) *P* is the property of a whole constituted of simpler components;
(ii) If *P* is a property of the whole composed of parts *a* and *b*, *P* is not *reducible* to separate intrinsic properties of *a* and *b*.
(iii) If *P* is a property of the whole composed of parts *a* and *b*, it is not necessary for *P* to contain information about *a* and *b* only if it also contains 'non-trivial' specific information about *a* and *b* separately.

Point (i) explicitly makes holism an integral part of the concept of inherence. As mentioned, the concept of reducibility in play in (ii) has to do with the fact that the possession of an inherent property by a whole does not *just* consist of the possession of certain non-relational properties by the components of that whole. Inherence can thus be regarded as the denial of mereological supervenience for properties, and the creation of a 'higher-level' property as certain parts constitute a whole (it, therefore, involves at least some aspects of what is known as 'emergence').

Seeing what (iii) means requires putting an essential *dispositional* element into the picture. Think, for example, of a two fair coin system about to be tossed, and a powerful demon who has decided to make the coins land on the same side—which one s/he will decide an instant after the toss. In this scenario, a disposition of the system to evolve so that the two coins will land on the same side can be attributed to the two-coin whole as an irreducible inherent property. This property describes what will happen to the individual coins, and so it is *about* the coins; however, it does not say anything specific about each specific coin—except for the fact that each coin will land on the same side as the other, which is 'trivial' in the sense that it *follows from* (and does not contribute to

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[8] That is, the fact that it is not the case that, for two entangled particles *A* and *B*, $\Pr^{AB}(x,y|i,j,\lambda) = \Pr^{A}(x|i,\lambda)\Pr^{B}(y|j,\lambda)$, where '*x*' and '*y*' are the outcomes of measurements of the same observable for *A* and *B*, respectively, '*i*' and '*j*' the setup of the measuring apparatuses, and λ the pair's state before measurement, which may encode some 'hidden variables'.

[9] It is interesting to notice that if the inherent property is not a relation, then particularism as defined by Teller is *not* violated by quantum systems. Also notice the connection between this and the debate about individuality: *if* the inherent property is a relation, then room is made for the view of identical particles (fermions, at least) as 'relationals' in the sense of Muller & Saunders (2008).

establish) a fact about the whole (notice that the demon's decision affects the coin pair directly, not via separate decisions about the individual coins). In a word, (iii) says that certain inherent properties (call them 'holistic') contain information about the parts of the whole exhibiting them without also containing the sort of information about the parts that can instead be expected to be available in what, following Teller, one may call the classical particularist setting. This feature of inherent properties, it is claimed here, is the key to understanding quantum statistics, exactly because it identifies the respect in which the quantum domain (and its statistics) differs from the classical one (and its statistics).

It is this holistic aspect of inherence, in particular, that has to do with the symmetry features, exhibited by quantum many-particle systems, that seem to call for a non-individual-based ontology: to put it simply, the statistically relevant properties of many-particle systems of quantum identical particles are inherent properties possessed by those systems as unitary wholes; as such, and in view of their essential dispositional aspect—peculiar to the quantum domain[10]—they describe the many-particle systems they belong to without saying anything about the specific particles, and only conveying information about (correlated) future measurement outcomes; hence, in a way that is insensitive to permutations of the particles (compare with the demon scenario).

Given the foregoing, the hypothesis can be made explicit that the *inherent properties exhibited by quantum many-particle systems are the unique cause of the peculiarities of quantum statistics* and, consequently, one does not need to question the particles' individuality, nor to revise one's understanding of probability distributions. But let us see this in more detail.

3.2. Inherent properties and quantum statistics

Statistics can generally be intended as a description of possible measurement outcomes. It is a widely shared opinion that in quantum mechanics the latter (in the majority of cases) do not *uncover* already possessed properties but rather *determine* the possession of actual properties. One might insist that measurements actualize certain propensities of quantum systems by making *dispositions* 'evolve into' actual ('categorical') properties,[11] or go in the opposite direction and attempt to reduce all dispositions to categorical bases. As mentioned (footnote 10), we can leave this as it stands, without embarking on a detailed discussion of dispositions. What is important to stress is the peculiar significance that the *measurement-relatedness* of statistical descriptions acquires in the case of quantum statistics.

Let us start by using again the familiar example of the two coins. Since these are classical objects, a property of the two-coin whole such as, for instance, 'one heads and one tails' is always reducible to two monadic intrinsic properties ('heads' and 'tails') possessed by the coins separately on each specific coin toss.[12] As a consequence, the property of the whole conveys information about which coin is in which state, and thus also includes a reference to specific identities. This entails that there are two ways in which the 'one heads and one tails' property can be possessed.

However, if it were possible to have the 'one heads and one tails' property of the two-coin system *without having separate properties for the two coins* (imagine the former property being a fundamentally 'dispositional aspect' not reducible to facts about the particles, in a way analogous to what happened in the earlier example of the powerful demon), then the property in question would be an inherent property of the whole that would be *about* the coins as parts of that whole without saying anything about any *specific* coin. A direct consequence of this would be that only one possible system would correspond to that property, as there would be only one way to exemplify it. Hence, unlike in the case of the 'fully classical' coins, *switching the coins would not give rise to a new total state*. Yet, crucially, the individuality of the coins would not be put into question.

This, the main claim of this paper is, is exactly what happens in the case of quantum many-particle systems of identical particles. For these, the statistics only describes what measurement results are possible for what systems. And, crucially, this description concerns inherent, pre-measurement holistic dispositional properties that contain no information about the individual particles. Hence, it should come as no surprise that, although the particles are individuals—and, therefore, it makes sense to ask which one will be in which state after measurement this is not something that one should look for in the pre-measurement situations described by the statistics. Indeed, for quantum many-particle systems one *only* has statistical information about the particles in the form (assuming again two-components and two-values systems) '1 and 2 *will* (be measured to)—or *would* (if measured)—have the same value for property P, namely, *x*' or '1 *will* (be measured to)—or *would* (if measured)—have opposite value to 2 for property P'. These qualitative descriptions too, *including the first* (see (Q1) and (Q2) above), can perfectly be taken to correspond to inherent properties understood as illustrated above. (This can of course be extended to all systems, independently of the number of their individual components: to see how, one just needs to conceive of the right sort of inherent properties describing possible measurement outcomes).

The proposed conjecture thus entails

(A) That for *all* many-particle systems and state-dependent properties particle exchanges do not give rise to new arrangements (i.e., the identities of the particles are not statistically relevant) *not* because particles are not individuals and consequently do not have well-defined identities. Rather, because *the particles' identities do not play any role in the determination of the states that are described by the statistics*.

(B) That one should not expect 'quantum analogues' of classical states such as (C4) (i.e., non-symmetric quantum states) to exist, because these would require a property-structure different from the one that—it is being claimed—is exhibited by quantum systems. That is, they would require specific values for observables corresponding to monadic state-dependent

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[10] No commitment to any strong view on dispositions is implied here, but only a weaker claim to the effect that in quantum mechanics measurement plays a crucial role. Emphasising that the theory tells us how certain systems will evolve upon measurement given the laws of nature is perfectly compatible, for instance, with Strawson's (2008) claim that there are no dispositions as everything that is real (including, therefore, causally relevant properties) is categorical. The scenario being suggested is also compatible with the opposite idea, examined among others by Blackburn (1990) and Holton (1999), that reality is essentially dispositional. Hence, intermediate positions are also allowed. In any event, there is no need to take a stance here.

[11] Work in favour of a dispositionalist, propensity-based, understanding of quantum properties was done by Popper (1957). For a more recent example, see Suarez (2007).

[12] Of course, this does not hold for the property 'one heads and one tails' intended as a description of any one outcome in a set of trials. What is important here, however, is the description of the ontological scenario behind *each specific actual* trial (thanks to an anonymous referee for emphasising the need to distinguish a result in a series of trials from the description of a specific real system).

> properties of individual particles, which however, simply do not exist before measurement.

Point (A) should appear clear enough given the foregoing discussion. It accounts for the permutation symmetry of quantum many-particle systems. A way to explain what point (B) exactly amounts to is the following. If holism is true of all quantum many-particle systems, it means that the correspondence between states (C1) and (C2) on the one hand and states (Q1) and (Q2) on the other is only an appearance due to the formalism.[13] While the former two effectively are states in which each particle is in a determinate state (i.e., possesses a value for the property under consideration as its own property), the latter two are instead states in which there is an emergent property of the composite system but no determinate states for the components, exactly in the same way as in the states described by (Q3) and (Q4). Clearly, if one *only* has inherent, holistic properties, states attributing equal values to the components ((Q1) and (Q2)) are unsurprisingly, and necessarily, 'complemented' by states describing 'opposite value' correlations, i.e., by entangled states ((Q3) and (Q4)), and not by non-symmetric ones.[14]

It can thus be concluded that the hypothesis that all statistically relevant properties of quantum many-particle systems are holistic properties inherent to the whole explains the peculiar features of quantum statistics while steering clear of the Received View on particle (non-)individuality. In fact, the explanation of quantum statistics suggested here *must* be deemed satisfactory if an account based on non-individuality is. Because the former differs from the latter only with respect to 'where particle identity is taken out of the picture', so to speak: i.e., in the 'content' of the relevant properties (the state-dependent properties of many-particle systems) rather than in the property-bearers (the particles themselves).

4. Further remarks

An important question concerns when exactly many-particle systems exhibit inherent properties. An answer is, of course, easily given in the case of entangled systems: for them, *interaction* between separate particles gives rise to a radically new entity, with completely new features—most notably, as we have seen, the non-factorizability of the total state. The inherent property is then just identical with the anti-correlation among the measurement outcomes for the separate particles which was not present before interaction. For non-entangled systems, however, this is not the case, and the postulated inherent property conveys exactly the same information as would be contained in intrinsic properties of the separate particles considered together That is, recalling non-entangled state-types (Q1) and (Q2)

$$|x>_1|x>_2 \tag{Q1}$$

$$|y>_1|y>_2, \tag{Q2}$$

there is nothing that can be said (in terms of future measurement outcomes) about particles 1 and 2 in these two-particle states that would not also be true if the particles constituted two separate one-particle states (i.e., $|x>_1$ and $|x>_2$ and $|y>_1$ and $|y>_2$)—and vice versa. Yet, in the two-particle case we are attributing an inherent property to the whole while denying that the two components have actual properties before measurement; and in the one-particle case we want to deny the existence of the inherent property (there is no whole it can be attributed to) while allowing for the possibility that the particles already are in state x or y before measurement. The risk exists, therefore, that simply by *describing* two or more particles as composing a unique whole (i.e., simply by describing them via the appropriate tensor product in Hilbert space) one is forced, on the present construal, to see monadic intrinsic properties ceasing to exist and making room for holistic, inherent properties.

The answer is that for non-entangled systems too it is interaction that gives rise to 'genuine wholes'. If there is no interaction, the use of the tensor product formalism just leads to the employment of the same linguistic expression for different ontological scenarios—with and without inherent properties of the whole respectively (notice, at any rate, that measurement outcomes are the same in the two cases).[15]

More details can be added on the basis of subjective preferences, for example suggesting that particles 'always' constitute wholes, for irreducible relations are ubiquitous. In any event, it does not appear necessary to deal with these issues further here.

One may dislike an ontology according to which inherent relations invariably emerge in quantum many-particle systems out of particles that possess separate monadic properties whenever they 'exist on their own'. However, the fact of inherence being pointed at should be regarded (at least if one agrees with the core of Teller's holist interpretation of the theory) as something peculiar to the quantum domain in general, and the present proposal simply extends to other systems claims that are already widely accepted for certain physical composites (i.e., entangled systems). If an explanation must be sought at all, it must regard the nature of entanglement *in general* rather than (or at least before) the present suggestion concerning quantum statistics. Surely, one may claim that holism is justified for entangled systems in view of their violation of factorizability. But, as argued earlier, one may also take the peculiar nature of statistics as equally in need of explanation, and the rejection of classical particularism and invocation of inherent properties to represent a readily available explanation for this.

Moving on to other types of worries, one may object that this proposal retains particle identity in name only, as properties do not, strictly speaking, belong to individuals anymore, while classically the whole point of attributing individuality to things is to say which objects have which properties. Reiterating claims already made at the beginning of the paper, it must first of all be responded to this that it was not the aim of this paper to defend the individuality of quantum particles directly, nor to provide arguments for or against any specific view of individuality. Moreover, first, particles are certainly attributed well-defined state-independent properties, that is, *specific instances* of the essential properties that make them individuals of a certain kind. These can certainly be deemed sufficient for the particles' individuality: it just requires not assuming the Identity of the Indiscernibles as a criterion of individuation (primitive thisness/haecceitas for properties or objects is always an option). Secondly, if it is correct to claim (following Muller & Saunders, 2008) that quantum particles are weakly discernible thanks to irreflexive

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[13] At least insofar as (Q1) and (Q2) and similar expressions describe genuine wholes produced by physical interaction. See the first remark in the next section.

[14] Recall the footnote towards the beginning of the paper pointing out the role played by a 'tacit assumption'—that there always exist separate properties for separate particles—in the identification of the impossibility of non-symmetric states as a problem.

[15] Thanks to an anonymous referee for pointing out this potential problem deriving from the formalism, as well as the need to say something about the dynamics according to which inherent properties 'emerge'.

relations holding between them, then, far from making individuality empty, this proposal (of course, once inherent properties are understood as relations) appears in line with the most recent 'empiricist-oriented' attempts to show that quantum mechanics does not in fact force us to give up particle individuality. Therefore, only by insisting that it is monadic state-dependent empirical properties that ought to individuate physical systems can one pursue this line of criticism; but such an insistence appears difficult to justify. Indeed, it would amount to sticking to the belief that classical individuality is the only form of individuality, which would make the whole enterprise of understanding quantum statistics on grounds other than non-individuality and quantum field theory a non-starter—which, in the present view, it clearly is not.[16]

In a different vein, one might insist on the presence of in principle meaningless surplus structure in the formalism of quantum mechanics. The following response could in that case be given: it can equally be maintained that classical mechanics is inadequate as a description of the objects in its domain because it is possible to describe the latter entities as entangled but entangled states are never realised in the classical world. In general, given any physical theory and its formalism, it is always possible to 'cook up' some form of surplus structure. In fact, what counts as surplus structure is not immediately determined given a set of statements/formulas, and ontological presuppositions are fundamental for interpreting the theory. This is essentially the reason why it is contended here that the ontological explanation provided in this paper succeeds where talk of inexplicable state-accessibility restrictions fails.[17]

Moving to the theory and its interpretation, another concern may arise. The first regards the relation between operators, states and properties. Usually, the Eigenstate–Eigenvalue link is assumed in employing the quantum theory, according to which a physical system actually possesses the property corresponding to a specific value for an observable if it is in an eigenstate for that observable corresponding to that value. This licenses inferences such as

$$\text{Prob(particle x has property P with value } \nu\text{)} = 1 \Rightarrow \text{ Particle x actually has property P with value } \nu \tag{2}$$

However, it was denied earlier that in states such as, for instance, (Q1) one has two particles each actually possessing a specific value for the given observable as an intrinsic property: the consequent in the above conditional must thus be deemed false. But in such states, the component particles have probability 1 of being detected as having that property: the antecedent is true. Therefore, the Eigenstate–Eigenvalue Link seems to be made invalid by the present proposal. The response to this might simply be generally to restrict the applicability of the Eigenstate–Eigenvalue Link to the total system. A better response is, however, that the Eigenstate–Eigenvalue link only applies to observables, and in the systems under consideration only symmetric operators related to the total system count as observables, and the operators corresponding to the single-particle properties are consequently excluded from the rule.[18]

One last point, which just needs to be mentioned, concerns standard quantum mechanics in comparison to its competitors. One could claim that interpretations/theories alternative to standard quantum mechanics (in particular, Bohmian Mechanics) also explain the statistics while preserving the idea that particles are individuals and so one does not need to consider this *n*th proposed modification to the theory. It is obvious, however, that standard quantum mechanics was assumed here as the default choice, and that the modification of the usual interpretation suggested—although non-negligible—is not so radical that it implies the departure from standard quantum mechanics. Hence, that a working explanation of quantum statistics along the suggested lines is available should in fact be regarded as something positive by all those who are not attracted, for independent reasons, by interpretations/theories other than standard quantum mechanics.

5. Conclusions

While the characteristics of quantum statistics are readily explained by giving up the idea that particles possess well-defined identities, on the conception of quantum particles as individual objects they represent a problem. Existing proposals alternative to the non-individuality view impute the difference in available states between classical and quantum statistics either to primitive restrictions on what states are accessible to what systems, or to peculiar facts about the probabilities with which the possible states occur in the quantum domain. However, the former type of explanation is little more than a transformation of the problematic evidence into a supposedly fundamental fact. The latter, instead, calls into play alleged differences in probability distributions between the classical and the quantum in a way that either does not work, or explains only partially, or is connected to other independent assumptions (i.e., the indistinguishability of all particles) that one may prefer not to make. The alternative to all this seems to be a form of skepticism regarding the metaphysical import of physics. Steering clear of this skepticism, but also of the non-individuality account of quantum statistics, a new alternative has been suggested in this paper, based on the conjecture that the peculiarities of quantum statistics are due to the fact that, unlike in the classical case—in which the statistics generally describes actual monadic properties of individual particles—what is described in the quantum case are inherent dispositional properties of the whole. It is hoped that this perspective on quantum statistics will be regarded as a plausible option worth exploring in more detail in future discussions.

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[16] I am grateful to an anonymous referee for pointing out to me the need to address this worry explicitly.

[17] It is interesting to notice that Huggett (1995) makes the same claim about surplus structure (using the example of the description in the 'language' of classical mechanics of a body moving faster than the speed of light) in the conclusion of a paper that attempts to deflate the relevance of metaphysics for the interpretation of physical theory entirely.

[18] I am very grateful to an anonymous referee for suggesting this response.

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