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ONTOLOGICAL ISSUES IN QUANTUM THEORY

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Abstract: In this paper, we examine the concept of *particle* as it appears in quantum field theories (QFT), focusing on a puzzling situation regarding this concept. Although quantum 'particles' arise from fields, which form the basic ontology of QFT, and thus a certain concept of 'particle' is always available, the properties ascribed to such 'particles' are not completely in agreement with the mathematical and logical description of such fields, which should be taken as individuals.

Keywords: Particles in quantum physics. Indiscernibility of quantum objects. Ontology of quantum theories.

QUESTÕES ONTOLÓGICAS NA TEORIA QUÂNTICA

Resumo: Neste artigo, examinamos o conceito de *partícula* tal como ocorre nas teorias quânticas de campos (QFT), enfocando uma situação enigmática acerca desse conceito. Embora 'partículas' quânticas surjam a partir de campos, que constituem a ontologia básica das QFT, e, assim, certo conceito de 'partícula' encontra-se sempre disponível, as propriedades atribuídas a tais 'partículas' não estão em completo acordo com as descrições matemática e lógica dos campos em questão, que são considerados como indivíduos.

Palavras chave: Partículas na física quântica. Indiscernibilidade de objetos quânticos. Ontologia das teorias quânticas.

1 Introduction

> "Then what is the ontology of quantum field theory? But what kind of quantum field theory? Actual or imaginable? [...] [E]ven within the category of actually existing quantum field theory, there are different versions: canonical formalism, functional formalism and algebraic formalism. Frequently people remind me that I should be sensitive to the different implications entailed by different formulations of quantum field theory. But in my opinion, in terms of ontological commitment, the existing different formulations make no difference at all."
>
> Tian Y. Cao [2003]

The Large Hadron Collider (LHC) is becoming ready for experiments (see [14]). There physicists aim to find, among other things, the Higgs boson, which according to the standard model (SM) of particle physics causes an interaction that justifies why particles have mass. At the LHC, physicists will accelerate beams of particles, such as protons, until near the speed of light, and after copious collisions (interactions), they will analyze their behavior. If all goes well, the events inside the collider should reproduce energies that were supposedly present a few moments after the Big Bang. To a certain extent, the progress of physics depends on finding the relevant features of elementary particles that have been previously postulated. Of course, new discoveries may emerge from the new experiments as well.

According to current physics, everything in the universe is made up from twelve basic fundamental particles (which give raise to approximately 200 particles), governed by four fundamental interacting forces. The standard model (SM) deals with three of them: electromagnetic, weak, and strong forces. At this stage, it constitutes our best understanding of how these particles and the relevant forces are related to each other. However, gravitation is still out of the picture. It is supposed that gravitation is also connected to a putative particle, called graviton. Thus, current physical theorizing at this level is based on the concept of 'particle'. It is not surprising then to find those who insist that "[t]he idea of a particle, [although] required modification with the advent of quantum theory, (...) remains central to scientific explanation" [12]. In this respect, on a realist reading, particles are the reality of present-day SM.

There is, still, a clear distinction between these *particles* and 'classical' (spatiotemporally characterized) particles. In fact, as they occur in standard, non-relativistic quantum mechanics, the particles of the SM that are classified as being 'of the same type' are conceptually indiscernible. This is not the case with classical particles. An interesting foundational problem then emerges regarding the formal (logical) characterization of these indiscernible objects.

Strictly speaking, if we consider the mathematical formulation of the SM, we just find *fields*. The standard model is a (mathematical) theory of fields: there are scalar fields, vector fields, tensor fields, spinors fields, and so on (see [6, p. 24]). In this context, particles are special situations of fields: they are certain excitations of quantum fields, or, as B. Falkenburg [8] notes, 'epiphenomena of fields'. An electron, for instance, is an electron-field, whereas a proton is a proton-field. Fields are the most basic entities referred to by the theory, and particles arise out of them. At first glance, we don't know what fields (and hence 'particles') are, for it depends on the particular interpretation of the theory, and how it is applied. If the ontology of a theory comprises the most basic kind of entity that the theory posits (see Cao [4]), the reduction of the concept of particle to the concept of field turns the ontology of QFT into an ontology of fields. However, as we noted, particles still emerge, and cannot be dismissed, at least as far as the discourse of the physicists is concerned. Michael Redhead [17] said that even in QFT "a particle grin" remains, yet it may just be an 'operational' concept of particle (more on this below).

The subject is controversial. In a recent pre-print, Casey Blood [2] stressed the fact that there is no evidence for particles in quantum physics. On his view, "all the particle-*like* phenomena can be explained by using certain not-widely-known properties of the wave function/state vector alone". By 'particle-like phenomena' he understands all properties "which have led physicists to postulate the existence of particles-mass, energy, momentum, spin, charge, the photoelectric and Compton effects, localized perception, particle-like trajectories, and atomic discreteness" which (according to him) can all be explained "by quantum mechanics alone", without recourse to particles. We believe that, as far as current quantum physics (QFT) goes, he is right. But, of course, his criticisms are directed against the *standard* concept of particle, described by classical physics. However, Redhead's point still stands: *some* concept of particle remains (whether such particles are thought of as 'epiphenomena of fields', 'field excitations', or whatever). Clearly, these 'particles' are theoretical concepts, motivated by physical intuitions. And although from the point of view of QFT, as noted, these particles can be 'reduced' to fields, they are neither like their classical counterparts nor like the fundamental entities of quantum physics.

The point can be extended further. After all, even fields may turn out not to be the very final ontological stuff of physics. For if string theory is correct, there are more fundamental objects, such as strings and p-branes. In turn, an algebraic version of QFT advances an approach that incorporates radically different assumptions. In the end, there does not seem to be a definitive answer to the question of the ultimate ontology of physics. Auyang [1] once noted that ontology is concerned "not with what exists as God ordains but with what exists as intelligible within the bounds of human understanding".[1] At best, we can try to make sense of the ontological commitments of various physical theories, understanding along the way physicists' discourse about such theories — if possible, within a clear logical framework.

Thus, it is important to acknowledge that contemporary physicists deal with a particle concept (although not with the classical one). This is the concept we are concerned with. We will speak of protons, neutrinos, electrons, and quarks as they appear in physical theories (albeit as a secondary species of objects), and we will consider which properties they have, which logic they obey. Without providing a complete account of these issues, for it may well be that they cannot be answered in full,[2] we focus on the issue of these particles' individuality. We argue that there is a discrepancy between the mathematical treatment of these objects as fields described within classical mathematics (and logic), and the supposed indiscernibility of the resulting particles. The tension is circumvented, in standard mathematics, only by assuming certain *ad hoc* symmetry conditions, such as the so-called Indistinguishability Postulate (see [10, *passim*]). Hence, we suggest that if these objects have the properties that most interpretations of quantum mechanics ascribe to them, there is a clear sense in which we may interpret them as entities governed by a non-classical logic.

2 Fields and particles

The history of the concept of particle and the emergence of the notion of field can be traced back at least to 19th century physics, but it will be not revisited here (see [8]). We just note that although the concept of particle

[1] The point, however, is controversial. For perhaps ontology should indeed deal with what exists independently of how it may be described by us; thus, dealing, as it were, with what God ordains. In contrast, the 'ontology of a theory' — to use Cao's Quinean words mentioned earlier — reflects what is posited by a given theory. But, at the fundamental level, such theory-dependent ontology is, ultimately, all we (can) have.

[2] For instance, given Heisenberg's uncertainty principle, it may not be possible to measure the whole quantum state of a quantum object with full certainty.

had strong defenders in the early formulations of quantum theory (such as Max Born), the concept of field emerged as the fundamental one. Nowadays, most physicists seem to accept an ontology of fields (on those occasions when they think about the issue). However, they do not always express themselves in this way, and as we noted above, they often speak in terms of *particles*.[3]

For our present purposes, two points should be stressed. First, in the characterization of particles (even as epiphenomena of fields), QFT uses standard mathematics (and logic). We shall discuss shortly what this apparently innocuous fact entails. Second, the concept of particle that emerges from this characterization is presupposed by contemporary physicists when they call certain objects *particles*. After examining the main features of this conception of particle, we will analyze the relationship it bears with relevant mathematical characterizations.

3 The metaphysics of quantum fields

To discuss the metaphysics of quantum fields,[4] we begin, as usual, with a discussion of how a quantum field is constructed.[5] Basically, a quantum field is obtained either by taking a classical field and quantizing it (field quantization), or by taking an assembly of indistinguishable (and non-interacting) quantum particles, described by the appropriate wave equation, and quantizing it (second quantization). In the latter case, we need 'to make' the quantum particles indistinguishable. This is the point where symmetry conditions enter.

Usually, the assumption is made that a classical field can be decomposed into the weighted sum of *modes*, each with a fixed wavelength. The energy of the field can then be decomposed so that each mode independently contributes to the field's total energy, in clear analogy with the case of the simple harmonic oscillator. For instance, following [18], consider the Klein-Gordon

[3]Why do physicists do that? Two tentative hypotheses can be mentioned here. Following Schrödinger, one can note that physicists have brought to quantum mechanics certain parts of the language of classical physics, based on the 'old' notion of particle as an individual, even though such physicists realize that that language does not mesh with "the real particle" (for a discussion, see [10, p. 246]). Another possibility is to insist on the tendency many humans have of dividing the world into objects (individuals) in order to speak of them (an alternative suggested by Toraldo di Francia [19]). Both are interesting hypotheses, but this is not the place to pursue them further.

[4]Further details are given in [10, Chap. 9].

[5]For a clear account of how to construct field operators for each type of particle, see, for instance, [16, Chap. 2].

field, which satisfies the equation of motion:

$$(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} + \mu^2)\psi = 0.$$

The motion of the field is represented in terms of modes, which corresponds to the quantization of infinite harmonic oscillators. The energy is given by:

$$E = \sum_k \eta_k(\hbar\omega_k) + constant,$$

where ω_k is the angular frequency of the mode k and η_k are the eingenvalues of the number occupation operators $N_k = a_k^\dagger a_k$, where the $a_k^\dagger$ and a_k are the raising and lowering operators for the harmonic oscillators [10, Chap. 9]. These excitation numbers η_k are usually identified with the number of *particles* in the k-mode with energy $\hbar k$ associated with that state of the field [18].

At this stage then the concept of particle enters. And it turns out, as Redhead [17] notes, that these 'particles', at least on a certain interpretation, do not have intrinsic individuality. In other words, these quanta cannot be regarded as *individuals* in the standard sense: for instance, given their lack of 'intrinsic individuality', no labels can be attached to them. How did we end up with 'particles' like that? And can a straightforward, standard semantics for the resulting quantum theory be provided? (As we will see, it is not clear that the answer to the latter question is positive.) We turn to these issues now.

4 Working with standard mathematics

Brian Davies points out that formal logic and set theory "are not important for mathematicians [presumably he refers particularly to applied mathematicians], the great majority of whom have never taken a course in formal logic and would not be able to write down the Zermelo-Fraenkel axioms of set theory" [7, p. 113]. In fact, mathematicians typically are not concerned with foundational issues, and usually do not delve into the (various) formal systems that have emerged from developments in logic and the foundations of set theory. But if this is the case for mathematicians, it is even more so for physicists. Not surprisingly, it is no simple task to convince physicists of the importance of studying the logical and mathematical basis of physical theories.[6] Needless to say, this is not our goal here. Rather, we intend only to highlight some consequences of working with standard mathematics and logic, and the assumptions that need to be made to circumvent some difficulties that emerge when this framework is used in the context of quantum mechanics.

The underlying mathematics of the SM is classical mathematics, hence the SM presupposes classical logic. But physicists use a mixture of various formalisms (as they call the mathematical theories they use), semi-classical approximations, and localized wave packets (among other components), in such a way that the underlying mathematics is not completely clear.[7] Despite that, we can assume that, from a formal point of view, all the mathematical details of the SM can be formulated in a fragment of Zermelo-Fraenkel set theory with the axiom of choice (ZFC) [9]. In ZFC, it is possible to construct, for instance, the theories of complex numbers, derivatives, differential equations, Hilbert spaces, and probability measure — and all that is required of the mathematical apparatus of the SM.

In particular, the underlying logic of ZFC is Leibnizian, that is, it is a logic of *individuals*. According to classical logic and mathematics, the identity relation and, hence, the concept of identity have a specific meaning, given by the *classical theory of identity*: if x and y are identical, they cannot be distinct entities, they are the *same* object, and count as being just one. Despite the redundancy and vagueness of this formulation, it expresses well the intuitive idea articulated by the relevant postulates.[8] But sometimes identity is presented, as in A. Zeilinger's formulation, by noting that "identity cannot mean more than this: being the same in all properties" ([21]). A difficulty then immediately emerges: if quantum 'identical' (that is, indistinguishable) particles are not the same, how can they share the same properties without violating classical logic? (We will return to this point below.)

Perhaps Zeilinger is referring to the way physicists use the word 'identity' in expressions like *identical particles*. Presumably, they mean agreement with respect to all *intrinsic* properties (see [11, p. 275]). But, alas, this is

[6] Recall the polemic between McKinsey, Sugar and Suppes with Clifford Truesdell and G. Hamel about the axiomatization of classical particle mechanics (see [20, p. 525]). A more recent discussion of the foundations of physical theories, including criticisms made by notorious physicists, can be found in [4].

[7] Some discussion of the lack of use of a clear mathematical theory in contemporary foundations of physics is provided in [13].

[8] It turns out that first-order postulates are not enough to characterize the diagonal of the domain of interpretation, the set where usually identity is interpreted, namely, the set $\Delta_D := \{\langle x, x\rangle : x \in D\}$, where D is that domain (see [10, §6.3.1]).

not the conception that underlies classical logic. On this conception, identity requires agreement with respect to *all* properties. Thus, the physicist's conception is ultimately just indiscernibility *relative* to intrinsic properties; that is, it is just a kind of 'relative identity'. The latter concept can be easily defined in a classical framework (e.g., in standard higher-order logic).[9]

But apparently this is not what Zeilinger is stating. He seems to refer to the (classical) *concept* of identity, and thus our criticism applies. It is important to realize that classical logic (with identity) is Leibnizian in the sense that it keeps some form of the Principle of the Identity of Indiscernibles (PII). In a second-order language (see the restrictions given in the previous footnote), this principle can be written as follows: $\forall F(F(x) \leftrightarrow F(y)) \rightarrow x = y$. According to this principle, all indiscernible objects are *the same* object. The converse of PII, the Principle of the Indiscernibility of Identicals, namely, $x = y \rightarrow \forall F(F(x) \leftrightarrow F(y))$, also holds, since if follows from the substitutive law of identity: it is a theorem of classical second-order logic. Furthermore, consider the property 'being identical with a', which is defined by $P_a(x) := x = a$, and suppose that this property is in the range of the variable F. In this case, even PII is a theorem of second-order logic [10, p. 255].[10] This is one of the main motivations to rule out the concept of identity from the logic of quantum objects and to work with them by supposing only a weaker relation of indiscernibility [10, Chaps. 7 and 8]. Philosophical reasons will also be offered below.

How can we accommodate indiscernible objects (such as quantum particles on a given interpretation) within standard mathematics and logic? Quantum physics, again on a certain interpretation, deals with indiscernible particles. Particles that arise from quantum fields — either free fields or interacting fields — must be indiscernible (assuming, once again, a certain interpretation). We can call an *individual* something that obeys the classical theory of identity mentioned above, that is, it is something identical only to itself, and to nothing else. Hence, if we have *two* individuals, they are distinct — as the converse of PII states. In fact, this way of making the point is more in accordance with Leibniz's own way of speaking:[11]

[9]In higher-order logic, such as simple type theory, consider the following predicate I (for 'intrinsic'): $I(F)$ holds if, and only if, F is an intrinsic property. The physicist's understanding of identity of particles can then be formulated: $x = y := \forall F(I(F) \rightarrow (F(x) \leftrightarrow F(y)))$, here the variables x and y range over particles, whereas F ranges over their properties. Clearly, if we suppose that there are also extrinsic properties, this formulation does *not* characterize mathematical identity.

[10]This can also be done if only a finite number of objects is being considered, which seems to be the case of physical theories.

[11]Leibniz often presented his principle in a 'negative way', pointing out that if certain

$x \neq y \to \exists F(F(x) \wedge \neg F(y))$.

In the context of quantum mechanics, the indiscernibility is achieved by supposing that the wave function satisfies something like:

$$\psi(x_1, \ldots, x_n) = e^{i\theta}\psi(x_{\sigma_{(1)}}, \ldots, x_{\sigma_{(n)}}),$$

here σ is an element of the permutation group of $\{1, \ldots, n\}$, n is the number of particles, and θ is a real number (see [3]). In other words, the particles are *named* $1, \ldots, n$, and the situation is such that any permutation of such indices does not amount to a different physical situation: the particles are indiscernible. In particular, the point applies to two relevant wave functions: the symmetric and the anti-symmetric, which correspond, respectively, to the two basic (detectable) kinds of particles, bosons and fermions. (The formalism, however, is compatible with a wide range of kinds of particles: para-particles of several kinds.)[12]

Even fermions, whose wave function is anti-symmetric, and which, due to Pauli's Exclusion Principle, *must* involve some difference, cannot be regarded as legitimate individuals. After all, individuals satisfy a number of (necessary) conditions — but not all of them are satisfied by fermions. (i) Individuals belong to a *kind*. A cube of scrapped metal, despite being made of the same material as a car, is still a cube and not a car. (It is sometimes said that a sortal concept should be used here, but problems emerge in the case of quantum objects; see [10, §8.7].) (ii) Individuals have properties. These properties may change, but the individual remains the same. (iii) Individuals have numerical identity. Usually such identity is expressed by a singular term, a *rigid designator* (e.g. a proper name or a definite description) in Kripke's sense. A rigid designator refers to *the same individual* in every possible world in which that individual exists. (iv) Individuals can always be distinguished from others, even of the same kind, which allows them to receive names, or labels. (v) The latter *label* the individuals in the sense that we can always (in principle) recognize the particular individual by its name (or by a definite description) as being *that* individual. (A sixth condition will be introduced shortly.)

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objects are *not* identical, then there must exist some quality (a given property) that distinguishes them. In Section 9 of his *Discourse on Metaphysics*, he notes that "it is not true that two substances can resemble each other completely and differ only in number [*solo numero*]".

[12] As is well known, the square of the wave function, namely, $|\psi(x_1, \ldots, x_n)|^2$, gives the relevant probability, and it does not matter whether the wave function is symmetric or anti-symmetric, for its square it is the same in both cases.

These conditions entail that, given a certain individual, which thus has certain properties, it is (in principle) always possible to claim that it is *that* individual rather than another. Names and definite descriptions express the individual's *genidentity*, to use Reichenbach's term (or its trans-temporal identity, or label-endurance).

Consider now two electrons (which are fermions) of a Helium atom in the fundamental state. According to quantum physics, the only distinction between them (which makes Pauli's Exclusion Principle hold) concerns their spin: in a given direction, one has spin UP, the other has spin DOWN. If they were individuals, we could name one of them Peter (say, the one whose spin is UP) and the other Paul (the one whose spin is DOWN). We would also be able to recognize, through an experimental procedure, which is which. However, as is well known, this is not something that can be done. Nothing in the quantum world determines which electron is Peter and which is Paul.[13] Thus, despite the difference between them, these electrons cannot be regarded as individuals in the classical sense. But this violates standard mathematics and logic: since there are *two* electrons, they *are* distinct objects; nonetheless, according to quantum mechanics, they are indistinguishable!

The difficulty also emerges if we consider the difference between a certain chemical compound, such as a molecule of sulfuric acid, H_2SO_4, and what we obtain if we replace (assuming that it is possible to do so) one hydrogen atom in that molecule by 'another' atom of the same kind. According to quantum mechanics, there is no physical difference between the two compounds. But since such compounds have 'different' hydrogen atoms, they are distinct. From the point of view of quantum mechanics, we are dealing with indistinguishable, but nonetheless different, compounds — a situation that is in tension with the classical conception of identity.

Consider, as yet another instance of the general difficulty, the process of ionization of a neutral atom which has just one electron in its outer shell. We ionize the atom by releasing one electron, obtaining, thus, a negative ion. (Note that expressions such as 'the electron' and 'one electron' presuppose the identity of the objects that are referred to.) By absorbing an electron, the atom then returns to its neutral state. Two questions immediately arise: First, what is the physical (rather than the metaphysical) difference between the two neutral atoms (before and after the electron's release)? According

[13] In order 'to save' PII, van Fraassen distinguishes quantum dynamical states from experimental events. As will become clear, this proposal can be accommodated by ours (see [13] and [22]).

to quantum mechanics (on a certain interpretation), the answer is clear: there is no difference whatsoever. Second, is the absorbed electron the same as the released electron? Once again, the answer is apparent: there is no fact of the matter here. But in this case, we cannot regard such electrons as individuals. After all, it is not clear that the concept of identity can be applied to them. We cannot assert that the two electrons — supposing that there are two of them — are distinct, given that it is unclear what the difference is between them. The possibility of giving them names is clearly not a sufficient condition for individuality. Definite descriptions, such as 'the electron which was released from the atom', presuppose identity; but it is doubtful that this expression really makes sense in this context.

It now becomes clear that we need to add a sixth condition to our characterization of individuals, namely: (vi) Individuals are '*extensional*', in the sense that at least some of the 'aggregates' to which an individual belongs change when an individual is replaced by another. For example, a football team formation is no longer the same formation if a player is replaced by another: it is a distinct team formation. Teams, however, remain the same despite changes in the players that constitute them. In this respect, aggregates of quanta resemble teams rather than team formations. Quantum aggregates do have components, but their components can be replaced (by components of the same type) without changing the aggregates. The H_2SO_4 molecule, like a team and unlike a team formation, does not change when a hydrogen atom is replaced by another. It is basically due to this sixth condition that even fermions cannot be regarded as individuals in the standard (classical) sense. No quantum aggregate to which a fermion belongs changes when a fermion is replaced by another: the aggregate remains the same.[14]

What should be done then? One possibility is to restrict the application of the concept of individual (which may be taken as primitive) only to some entities,[15] while insisting that the concept of identity holds in general. Formally, this move can be made by assuming that $x = y$ is a well-formed formula (and so is its negation), but the predicate 'is an individual' only

[14] Note that although we may not be able to identify explicitly certain objects of classical mathematics, on a standard interpretation they are individuals. Consider the following two subsets, (1, 2) and (3, 4), of the set of real numbers, and let us assume the axiom of choice. Since, with this assumption, the set of real numbers is well ordered, these subsets have each a least element, which are distinct. We are unable, however, to exhibit explicitly the well-ordering in question by a formula. Quanta, on the interpretation we have been invoking here, behave differently: the issue is not whether we are able or not to distinguish them — they are indistinguishable even in principle.

[15] For example, in the case of concrete individuals, they are expected to satisfy some physical conditions, such as presenting decoherence.

applies to certain objects. In this way, the postulates of identity hold for those entities that obey the predicate 'is an individual', and it is possible to continue to use standard logic and mathematics.

But this move raises some concerns. First, even if the postulates of identity apply to individuals, the idea that we can speak of non-individuals (those who are *not* individuals) as being equal or different presupposes that *in some way* they are discernible. Otherwise, it is unclear what is meant by $x = y$ (or $x \neq y$) as applied to such non-individuals. Second, in the context of quantum mechanics, this alternative resembles the introduction of hidden variables — items that go beyond the quantum-mechanical description and which are supposed to settle certain issues that are left open by quantum theory alone. Presumably, such 'hidden variables' would allow one to distinguish non-individuals. But there are well-known difficulties with the introduction of such variables in quantum physics (as the Kochen-Specker theorem indicates). Third, this alternative is not significantly different from restricting mathematical discourse to a particular ZFC structure in which just some properties and relations are considered. In this case, it is easy to define the concept of identity relative to this structure (invariance by its bundle of relations) by noting that the objects a and b are identical if and only if they share all the selected properties and relations — or, equivalently, if there is an automorphism h of the structure such that $h(a) = b$.[16] However, rather than classical identity, we have here indiscernibility relative to a structure (or to a bundle of properties and relations). Finally, if the structure in question is built in ZFC, it can always be extended (by adding adequate predicates and relations) to a rigid structure, whose only automorphism is the identity function. In other words, *outside* the structure, that is, in the 'whole ZFC', we can show that any object described in ZFC is an individual. (This holds for all usual set theories and higher-order logical systems.) The attempt to 'confine' individuals to a particular structure is just a somewhat artificial way of avoiding reference to certain properties.[17]

These considerations suggest that van Fraassen's distinction between quantum dynamical states and experimental events can be interpreted as stating that the former represent what a vector or a statistical operator stands for — that is, things *embedded* in quantum mechanics, whose evolution is governed by dynamical laws — while events are described only 'from outside' the formalism of quantum theory. In particular, PII would

[16]Incidentally, this is Quine's way of 'defining' identity.

[17]We are simplifying the discussion here, given that the concepts of distinction by automorphisms and distinction by a formula are not the same. But we shall not pursue this point further here.

be preserved only outside the formalism. That is, while dynamical states are described *within* the formalism of quantum mechanics, events are *extra-theoretic* entities that satisfy the probability calculus (for further details, see [13]).

5 Is identity a fundamental concept?

Why is such a strong commitment to identity ultimately needed? Perhaps Toraldo di Francia is right in suggesting that we have an inclination to reason and speak about the world as being formed by objects conceived of as individuals. Classical logic, standard mathematics, and classical mechanics seem to be reinforced by this tendency. But if, as Zeilinger insists, identity amounts to being the same with respect to all properties, then perhaps none of us are individuals, for our properties are constantly changing, and strictly speaking, we lack a well-defined catalog of properties that identify us. Leaving aside the old controversy about essential properties and ideas about substratum, perhaps we can say that, despite their constant changes, our properties are unique to us. But, clearly, this is a metaphysical supposition.

In the end, Hume was right in noting that the key reason why we are able to (re-)identify objects over time is habit. In fact, there is no logical way of proving that the Barack Obama we saw yesterday on TV is the same we saw the week before, although it is easier to suppose that this is the case. Ultimately, similarly to inductive inferences, the identity of an object over time has no logical grounds. This seems to be particularly the case for electrons and other quantum objects.

On reflection, the notion of identity as applied to empirical objects may be just a useful tool. It is easy to assume the identity of Barack Obama over time — as well as of other persons and physical objects. In fact, it is hard to imagine what the physical world and the theories we construct about it would be like without such a hypothesis. The latter may be seen as a metaphysical assumption we impose on our understanding of the world. But this assumption requires ontological commitments that are strongly questioned by a reasonable interpretation of quantum physics.

Perhaps one way to proceed, from the point of view of the foundations of physics, and for those who have a realist inclination, is to wake up from the classical slumber and apply quantum ideas more generally — including those involving indiscernibility — to the world as a whole. A difficult task, no doubt, but a path worth exploring. Interestingly, this path can also be explored by empiricists, who do not take quantum mechanics as being true, or even approximately true (see [22]). In examining the implications of (a certain interpretation of) quantum mechanics to the (lack of) identity of ordinary objects, we may be able to understand how the observable world would be if quantum mechanics were true — no doubt, a valuable task as well.

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