Chapter 9
Quantum Objects

9.1 Introduction

It has been argued that non-relativistic quantum mechanics for systems of many components raises profound challenges to any metaphysics that seeks to explain the world in terms of self-subsistent individuals (e.g. Ladyman and Ross 2007). It is claimed that quantum particles are not individuals since the usual identity criteria used in ontology seem to fail when applied to them. The standard criterion adopted by philosophers on this matter is Leibniz's Principle of Identity of Indiscernibles (PII). This principle asserts the identity of two objects if they have exactly the same properties. Two objects identical in every respect are not two different individuals (see French and Krause 2006 for refinements. Also, see Teller 1983, French and Redhead 1988, and Saunders 2003). Identical particles in classical mechanics, for instance, share the same intrinsic properties but can be distinguished by their trajectories in spacetime. Something similar occurs in everyday life: in a race of several intrinsically identical cars we can still individuate them if we can keep track of their trajectories. So, PII allows us to claim that there are different cars in the race.

In the quantum world things seem to be different. It is not possible in general to assign well-defined trajectories in spacetime to quantum objects. Two photons or two electrons in an entangled state cannot be individuated by singular spacetime features: their location probability densities are the same. If the photons were prepared in a particular state of polarization, this state is characteristic of the pair, not of the components. These considerations also hold if the quantum particles are in a bound state. If we have two electrons, for instance in an helium atom, they have exactly the same position distribution of probabilities. They also share the same energy eigenstate. Not only all intrinsic properties are identical but also all relational properties seem to be indistinguishable. The entangled state function is completely symmetric with respect to both particles, so not even the different spin orientations are useful to individuate the electrons. It seems completely impossible to distinguish

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the two electrons according to any version of the PII. Should we conclude that they are not individuals?

9.2 Identity and the Quantum World

Let us try to characterize the quantum indiscernibility more formally. Quantum particles are usual called 'identical' if they share in common all their constant properties, such as mass, charge, spin and so on: that is, if they agree in all their state-independent or intrinsic properties. The same applies to classical particles. In addition, quantum particles are indistinguishable if they satisfy the so-called indistinguishability postulate (IP).
(IP): All properties represented by operators $\hat{O}$ must commute with all particle permutations $\hat{P}$:

$$[\hat{O}, \hat{P}] = 0.$$

The IP expresses the requirement that no expectation value of any property is affected by particle permutations. So, if Ψ_{12} is a two-particle state and $\hat{P}$ an operator that interchanges the particles 1 and 2, such that $\hat{P}\Psi_{12} = \Psi_{21}$, then the particles are indistinguishable if

$$\langle \hat{P}\Psi_{12}|\hat{O}|\hat{P}\Psi_{12}\rangle = \langle \Psi_{12}|\hat{O}|\Psi_{12}\rangle, \quad \forall\hat{O}, \forall\Psi_{12}.$$

Bosons are then clearly indistinguishable and entangled fermions are as well. Does this entail that they are not individuals? Not necessarily. One can, for instance, adopt a non-standard version of the theory such as Bohm interpretation,[1] where trajectories in spacetime are ascribed to all particles allowing for discernibility and individuation. The price to be paid, in such a case, is the burden of the extra assumptions of Bohm's theory and a more complex formalism, but so far this move is neither hampered by logic nor experience.

One also can resist the conclusion of the PII. Perhaps indiscernibility does not imply identity and lost of individuality. After all, even if the particles are indistinguishable, the number of them is not in question. Might cardinality amount to individuality in the quantum realm? Actually, in some occasions, even in ordinary life, we deal with situations where we adopt cardinality as a criterion for individuality. Imagine that I have a sum of money, say $ 300. I go to the bank and deposit my bills. Surely, I still have exactly the same amount of money when I check my electronic account, but there is no point in trying to identify some number in my

[1]It would be more correct to consider Bohm's approach to quantum physics as a different theory from QM because additional dynamical variables are considered and new entities introduced, namely the famous pilot wave.

computer with the original bills. I can convert my money into cash if I want. If I do that, the amount will still be the same amount that I deposited. But the individual bills will differ. So, I might say that the continuity in cardinality has preserved the identity of my amount of money, although not that of the individual bills. Perhaps it is possible to say something similar of the system of entangled quantum particles: the system, as a whole, is preserved as an individual, although not the specific components.

Another famous example is Max Black's two-sphere problem (Black 1952): two intrinsically indistinguishable spheres in a fully symmetrical universe are indiscernible. Should we conclude that there is just one sphere? No, there are two spheres in that universe, but they are indistinguishable. Muller and Seevinck (2009) observe: "Similar elementary particles are like points on a line, in a plane, or in Euclidean space: absolutely indiscernible yet not identical (there is more than one of them!). Points on a line are categorical relationals, categorical weak discernibles to be precise. Elementary particles are exactly like points in this regard."

Whether quantum particles are individuals or not depends on what we understand by an 'individual', and as these examples show, the PII is not the only criterion that we can follow in this respect. Quine (1976), for instance, suggests the following criteria:

> A sentence in one variable specifies an object if satisfied by it uniquely. A sentence in one variable strongly discriminates two objects if satisfied by one and not the other. A sentence in two variables moderately discriminates two objects if satisfied by them in one order only. A sentence in two variables weakly discriminates two objects if satisfied by the two but not by one of them with itself.

Based on these ideas, Muller and Saunders (2008) define absolute discernibility in a given language L as follows:

1. Two objects a and b are absolutely discernible in L iff there is a monadic predicate M in L such that $Ma \wedge Mb$ or $\neg Ma \wedge Mb$.
   Additional notions of relative and weak discernibility are given by:
2. Two objects a and b are relatively discernible iff there is an open formula F in two variables in L such that $F(a, b) \wedge \neg F(b, a)$.
3. Two objects a and b are weakly discernible iff there is an open formula F in two variables in L such that $F(a, b) \wedge \neg F(b, b)$.

Let us consider now the following open formula: ' …has opposite spin in direction z to…' (Saunders 2006). Electrons in the helium atom are weakly discernible in the above sense: we can say that they have not the same spin state, although we cannot say which state corresponds to each of them. This type of weak discernibility is enough for individuation in non-relativistic quantum mechanics (Perez-Bergliaffa et al. 1996), but things go worst if we move to quantum field theory. Quantum field theory (QFT) is the ultimate expression of quantum mechanics so it is important to understand the ontological status of particles in this theory if we want to clarify whether quantum particles are individuals or not.

What we call ‘particles’ in quantum mechanics are seen merely as excitations of a quantum field in QFT. These excitations or ‘quanta’ can be aggregated and counted but not enumerated in the sense of labeled. The world, in this view, is a collection of quantum fields existing in spacetime. The vacuum state $|0\rangle$ of these fields can be excited to form a Fock basis of the quantized field:

$$|1_k\rangle = a_k^\dagger |0\rangle. \tag{9.1}$$

Each application of the operator $a_k^\dagger$ adds a quantum excitation to the state k. Successive applications of the operator $a_k^\dagger$ yield:

$$a_k^\dagger |n_k\rangle = (n+1)^{1/2} |(n+1)_k\rangle. \tag{9.2}$$

Similarly, the operator a_k removes quanta:

$$a_k |n_k\rangle = n^{1/2} |(n-1)_k\rangle. \tag{9.3}$$

In Minkowski space, a preferred basis can be constructed using the specific symmetries of this space (the Poincaré group). Then, if $N_k = a_k^\dagger a_k$ is the operator number of particles, we get

$$\langle 0 | N_k | 0 \rangle = 0, \qquad \text{for all } k. \tag{9.4}$$

This means that the expectation value for all quantum modes of the vacuum is zero: if there are no particles associated with the vacuum state in one reference system, then the same is valid in all of them. In curve spacetime this is not valid any longer: general spaces do not share the Minkowski symmetries, and hence the number of particles is not a relativistic invariant. Since in general spacetimes there are different complete sets of modes for the decomposition of the field, a new vacuum state can be defined:

$$\bar{a}_j |\bar{0}\rangle = |0\rangle, \quad \forall j, \tag{9.5}$$

and from here a new Fock space can be constructed. The field $\phi(x)$ can be expanded in any of the two basis[2]:

$$\phi(x) = \sum_i [a_i u_i(x) + a_i^\dagger u_i^*(x)], \tag{9.6}$$

[2]For simplicity I consider a scalar field.

and

$$\phi(x) = \sum_j [\bar{a}_j \bar{u}_j(x) + \bar{a}_j^\dagger \bar{u}_j^*(x)]. \tag{9.7}$$

Since both expansions are complete, we can express the modes $\bar{u}_j$ in terms of the modes u_i:

$$\bar{u}_j = \sum_i (\alpha_{ji} u_i + \beta_{ji} u_i^*), \tag{9.8}$$

and conversely,

$$u_i = \sum_j (\alpha_{ji}^+ \bar{u}_j - \beta_{ji} \bar{u}_i^*). \tag{9.9}$$

The coefficients α_{ij} and β_{ij} satisfy the relations

$$\sum_k (\alpha_{ik} \alpha^* jk - \beta_{ik} \beta_{jk}^*) = \delta_{ij}, \tag{9.10}$$

$$\sum_k (\alpha_{ik} \beta_{jk} - \beta_{ik} \alpha_{jk}) = 0. \tag{9.11}$$

The operators on the Fock space then can be represented by:

$$a_i = \sum_j (\alpha_{ji} \bar{a}_j + \beta_{ji}^* \bar{a}_j^\dagger), \tag{9.12}$$

and

$$\bar{a}_i = \sum_i (\alpha_{ji}^* a_i - \beta_{ji}^* \bar{a}_i^\dagger). \tag{9.13}$$

An immediate consequence is that

$$a_i |\bar{0}\rangle = \sum_j \beta_{ji}^* |\bar{1}_j\rangle. \tag{9.14}$$

Since in general $\beta_{ij} \neq 0$ the expectation value of the operator $N_i = a_i^\dagger a_i$ that determines the number of quanta is:

$$\langle \bar{0} | N_i | \bar{0} \rangle = \sum_j |\beta_{ij}|^2 \neq 0. \tag{9.15}$$

This surprising result means that the number of quanta of the field (particles) is different for different decompositions. Since different decompositions correspond to different choices of reference frames, we must conclude that different observers detect a different number of quanta (particles). These particles activate detectors in some reference systems, but not in others. They are essentially a frame-dependent feature of the field. If we accept the extended idea that whatever exists objectively cannot depend on our choice of a particular reference system, then the assumption that particles are self-subsistent individuals falls apart.

9.3 Ontic Vagueness?

In Chap. 2 we characterized vagueness as a kind of semantical indeterminacy. Some authors have seen in the peculiarities of quantum objects an indication of ontic vagueness. Lowe (1994), for instance, proposes to consider electrons as vague individuals. He points out that if an electron a is captured by an atom in an ionizing chamber in such a way that the atom becomes a negative ion and then it reverts to its previous state by emitting an electron b, there is no objective fact of matter as to whether or not a is the same electron as b. Lowe points out that the impossibility to identify whether $a = b$ is not an epistemic issue but a direct result of the basic laws of quantum mechanics. According to QM the electrons in the atom enter into a entangled state in which although their number is determinate, their identity is not. Therefore, there is no fact about whether the emitted electron is the same electron that was captured: it lost its identity when entered into a quantum superposition with the other electrons. The indeterminacy of $a = b$, Lowe thinks, amounts to a case of ontic vagueness.

There is a well-known argument against the existence of vague objects by Gareth Evans (1978). The argument goes like this: Let us assume for the sake of reductio, that it is indeterminate whether $a = b$, where 'a' and 'b' are precise designators, in a semantical sense. Then b definitely has the property that it is indeterminate whether it is identical with a, but a definitely lacks this property (since $a = a$ is surely not indeterminate), hence it is false that $a = b$, contrary to the assumption that it is indeterminate. The upshot is that if '$a = b$' is indeed indeterminate in truth value, then either 'a' or 'b' or both must be an imprecise designator. Hence, this would be a case of semantic vagueness, not ontic.

Lowe response is that an essential step in the argument is the move from the determinacy of the self-identity of a, say, to the claim that a definitely lacks the property that it is indeterminate whether it is identical with a (which is possessed by b). However, the latter property cannot be determinately distinct from the property of being indeterminate whether the object is identical with b, since the two properties differ only by a permutation of a and b and it is indeterminate whether $a = b$ by assumption. Hence the possession by either a or b of an identity involving property such as these cannot serve to determinately differentiate the two.

French and Krause (2003) argue that there is another kind of vagueness involved, which is associated with the lack of individuality of the particles (something that is not disputed by Lowe). They argue that because in quantum statistical mechanics, arrangements of particles over states which result from permutations of the particles cannot be counted as distinct, contrary to the case of classical statistical mechanics. As a consequence, quantum particles themselves cannot be considered as distinct and they lack of individuality in this sense. The result, they claim, is in accordance with the Fock representation of QFT, where the particles are not labeled. There is an assignment, nevertheless, of definite cardinality to the quantum state of the field, where the number of quantum excitations or 'quanta' corresponds to the number of non-individual 'particles'. Hence, they state that "we can have a determinate number of quantum objects in a given state without these objects possessing definite identity conditions [...] it is because of this lack of self-identity that the objects can be described as vague, in perhaps the most fundamental sense one can imagine."

Although I think that French and Krause are right in their analysis of the lack of individuality of the quanta in QFT, I do not agree with the commitment with ontic vagueness. What QFT clearly shows, as I explained in the previous section, is that what we consider in QM as 'particles' are actually excitations of the field in some specific reference frame. These excitations are then not "objects" as claimed by French and Krause, but relational properties of the field. And they are not vague at all, because the theory is completely clear about how to assign such properties to the field. The fact that the property in question, the number of discrete excitations of the field, is not a relativistic invariant is not enough to state that there is ontic vagueness. We have plenty of relational properties in our physical theories. If we reify them, making a category mistake, we might conclude that velocities are "non-individual objects". According to the best available theory, i.e. QFT, quantum particles are not objects at all, but just a feature of a different entity, the quantum field. The reason why Evans argument fails when applied to quantum particles is that such particles are not entities or objects that exist independently of a specific choice of a reference frame. The clause " '*a*' and '*b*' are precise designators" is false, then the argument cannot proceed. We do not live in a world of particles, we live in a world of fields, where particles appear as modes of excitations in the fields. It might be strange and counter-intuitive to understand particles as properties and not objects, but this should not hinder us if it is implied by well-established physics. Vagueness on these issues still belongs to our thought about the world, and not to the world itself.

9.4 Realistic Quantum Ontology

If particles are not the basic ontological referents of modern physical theories, what should be considered by a scientifically informed realist as the best ontology? Ladyman and Ross (2007) think that if we cannot adopt particles because they are not individuals, then the next step is to move towards structures. According to them a metaphysics of self-subsistent individuals is at odds with physics and should be abandoned in favor of a metaphysics of structures. In this view, what we call individuals are just nodes in the structure and completely dependent on it. This is ontic structuralism, a popular view at the time of writing these lines.

I confess that these arguments are not convincing to me. They seem to be the result of a too strong commitment with standard QM. In QFT particles are not dealt as individuals but as features of the quantum fields and relative to some specific choice of mode decomposition of the field that is frame dependent. Matters of existence should not be solved just counting or individuating with respect to some reference system, but considering true invariant properties and their referents. In this sense it is the energy-momentum complex and its mathematical representation through a second-rank tensor field that provides an objective indicator of independent existence. Contrary to the excitations of the field, that depend on global modes defined over the whole spacetime, the energy-momentum of the field is defined locally through a tensor quantity. For a fixed state $|\psi\rangle$ the results of different detectors when measuring the expectation value $\langle\psi|T_{\mu\nu}|\psi\rangle$ can be related by the usual transformation laws of tensors. In particular, if $\langle\psi|T_{\mu\nu}|\psi\rangle = 0$ in one reference system, the energy density of the quantum field will be zero for any reference. This situation is quite different for particles, that might be detectable or not in the same region of space by different observers in different states. This clearly points out that the ontological import is in the quantum field, not in the particles. And it is not neither in the structure, since the structure emerges from the relations of the fields.

It might be objected that in the case of Minkowski spacetime all fields are in the vacuum state and then $\langle 0_{\rm M}|T_{\mu\nu}|0_{\rm M}\rangle = 0$. But an accelerated observer in this spacetime actually should detect thermal radiation (Davies 1975, Unruh 1976). In the accelerated frame it is also valid $\langle 0_{\rm M}|T^{acc}_{\mu\nu}|0_{\rm M}\rangle = 0$, so the thermal radiation seems to violate energy conservation. But this is a wrong conclusion originated by considering only a part of the system. The whole system is the accelerated detector plus the field in the vacuum state. The field couples with the accelerated system producing a resistance against the accelerating force. It is the work of the external force that produces the thermal bath measured by the detector in the comobil system. The same radiation is not measured by a detector at rest, since it is not coupled with the field. I remind here that a vacuum state of the field does not correspond to the absence of field, but to the absence of discrete excitations of the field. The example just shows the reality of the field, even when there are no excitations. The excitations themselves, the quanta, can be present in one system and not in other, according to the state of the system with respect to the field.

When curvature is present in spacetime, inertial frames will be associated with free-falling systems and in general not unique choice of the vacuum state can be made to express the field. So, different detectors located in different reference systems will detect different numbers of particles. Polarization of the vacuum by event horizons results in Hawking radiation that is detectable in the asymptotically flat region of spacetime, but such radiation is not seen by an observer falling freely into the black hole. In general, there is not simple relation between $\langle N_i\rangle$ and the particle number measured by different detectors (Birrell and Davies 1982). The ontological status of particles in QFT in curve spacetime is that of a complex relational property between fields and detectors. The ontological substratum, however, is provided by the fields. Remove them, and nothing is left: no energy-momentum, no excitations, no expectations, no structure. I conclude that quantum objects are quantum fields over spacetime. In the next chapter I will discuss the status of spacetime itself.

Summing Up Non-relativistic QM for systems with many components provides a strong argument against the individuality of quantum particles. This is fully realized in quantum field theory, where the particles are interpreted as discrete excitations of quantum fields existing over spacetime. These arguments against the individuality of quanta, however, do not entail the existence of vague quantum objects. The ontology of quantum field theory is an ontology of fields. These fields are endowed with definite properties albeit some of them are frame-dependent. Quantum excitations are some of these relational properties, when curvature for spacetime is allowed. Relational features of certain entities do not imply ontic vagueness. At most, some people can talk vaguely about them.

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