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Peer Review

Review of: "The Non-Reflexive Formulation of Quantum Mechanics: the Whys and the Hows"

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In this article, Prof. Krause presents the motivations for his long-term research on the non-reflexive formulation of quantum theory and provides a brief summary of the ideas underlying this formulation. Relevant references are given in the bibliography for the benefit of readers interested in a more in-depth study of the topics covered.

I confess that I was not aware of this line of research and have therefore benefited greatly from this compendium, which I find admirably clear and direct in its style. I must say, in my defence, that not being a philosopher of science, I have never applied myself to a thorough examination, from a logical point of view, of the conceptual categories involved in the construction of physical theories. For the same reason, I do not feel qualified to write a review of this article. I would therefore like these lines of mine to be considered for what they are, that is, as the commentary of a person who uses physical theories every day for his work. A person, therefore, whose interest in a new formulation is strictly linked to its practical convenience in terms of both description and, possibly, application.

From this pragmatic perspective, my main doubt concerns the relationship between quantum entities and space, a relationship that does not seem to me to be sufficiently taken into account by the line of reasoning of the article (for example, page 9). The complex intertwining of Leibniz indiscernibles, spatial position, and distinguishability of particles is detailed in the nowadays classic and well-known work of Howard, so I limit myself here to some subsidiary remarks.

First, when we talk about quantum entities like electrons, we are actually talking about packets of conserved physical quantities exchanged between two consecutive interaction vertices, rather than persistent objects. The packets entering vertex A are distinct from those exchanged between vertices A and B, and the latter are distinct from the packets leaving vertex B. In this sense, these non-objectual

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entities are not re-identifiable in different contexts (even when provided with the same internal quantum numbers), as correctly pointed out in the article. The situation here is analogous to that found in classical physics with concepts like "volume elements in a fluid", in the sense that the matter enclosed in a given volume is continuously changing or, to put it another way, the single "volume element" is not a substantial entity. It seems to me that the challenge of building a formalization of quantum theory without labels associated with particles is based on the need to logically formalize this property of non-re-identifiability.

However, this choice may be too radical and equivalent to throwing the baby out with the bathwater. In fact, the second relevant property of particles is to be charge carriers and, therefore, sources of fields (electric, gravitational, etc.); or mediators of interactions between charges, as is the case for photons, for example. This fact implies that different quanta can interact in different places at different times, participating in spatially and temporally distinct interaction vertices, by virtue of their property of representing distinct field sources or interaction mediators. Thus, the state of the electromagnetic field with an exactly definite number N of photons represents the condition for having N photon absorptions (events) in N distinct space-time regions.

Similarly, from a generic layer of atomic orbitals with N electrons, N electrons can be extracted, each susceptible to separate interaction with other particles, thus giving rise to the possibility of a maximum of N spatially and temporally distinct interactions. Thus, it is the possibility of different space-time positions that operationally defines N. In my view, this aspect of the problem underlines the relevance of space-time position in the issue of the countability of particles.

Of course, this does not imply the existence of trajectories of individual particles, and therefore of a distinguishability of the N quanta considered in these examples. The situation here is similar to that which occurs in classical physics with the harmonic components of a sound, which are distinguished by specific characteristics (frequency and amplitude) but at the same time "fused" in the single sound phenomenon. And yet, they are separable by means of appropriate procedures (for example, coupling with a Helmholtz resonator of appropriate natural frequency). Thus, in the Hamiltonian of the helium atom, the electron-nucleus and electron-electron interactions are invariant both in form and numerically with respect to the permutation of the electrons (which are therefore, in this sense, indistinguishable). However, each electron is the source of a distinct electrostatic field, and this source has, at least as a Heisenbergian potentiality, a distinct position (although defined with an uncertainty in accordance with the uncertainty principle). This position becomes actual if the electron is extracted from the atom,

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separated, and made to interact with a suitable system. Now, the theoretical choice of eliminating the labels of the particles, and with them their spatial position, hides this possibility of actualization. That is, precisely the quantum discontinuity, which represents the element of quantum theory that has no analogy in classical physics. The fear, in other words, is that a representation in terms of occupation numbers alone hides the physical reason for the indistinguishability of the particles, that is, their interchangeability in the interactions mediated by the fields of which they are the sources.

On a more "applicative" side, one could say this: it is certainly possible to represent the Hamiltonian of the helium atom in the basis constituted by its orbitals (the field modes). And, given the combinatorial rules that connect these orbitals to the states with a definite occupation number of the theory proposed by the author, it is therefore possible to express the Hamiltonian in terms of creation and annihilation operators acting between the latter. However, it should not be overlooked that the starting point of the construction, represented by the orbitals, is obtained by solving the Schrödinger equation with the Hamiltonian expressed in the positional basis. That is, in the basis in which the particles are distinguished by their spatial position, even if they are not re-identifiable in the previously stated sense.

So the question is whether choosing a non-reflexive representation, centered on non-re-identifiability, which eliminates particle labels from the outset, does not risk throwing away the truly interesting physics that underlies, among other things, the phenomenon of non-reflexivity itself.

Finally, allow me to make two more technical clarifications.

1) The Hamiltonian operator of the helium atom [equation (1)] lacks the electrostatic interaction term between the two electrons.

2) Page 9, end. If the two electrons are placed in spatially separated places and have never interacted in the past, they cannot enter into an entanglement relationship. Therefore, their total wave function is the mere product of the two distinct wave functions: Psi_12 = phi_1 * chi_2. That is, it cannot be Psi_12 = phi_1 * chi_2 ± phi_2 * chi_1 or similar.

This fact, which can be found in every manual and is well known to those who deal with quantum technologies, is the consequence of the circumstance that the statistical correlations between spatially separated subsets are established at the level of their past interaction in their common source (this interaction dissolves when the distance between the particles increases). For example, the photons of Aspect's classic EPR experiment originated from the cascade decay of single excited calcium atoms. A terrestrial electron cannot be entangled with a similar one placed in the Andromeda galaxy.

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It is true, however (and this could be an explanation for the confusion), that if they were permuted, their total wave function would change sign.

Declarations

Potential competing interests: No potential competing interests to declare.