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Some Remarks on the Notion of Separability Within the Creation Discovery View

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Abstract In this paper we present Aerts' vessels of water model which violates Bell inequalities, and discuss how this fits in the Creation Discovery View in the context of the Operational Quantum Logic approach. We analyze the 2 different ways in which correlation is classically observed, either as pre-existing 'independent of measurement' or established by sending a signal, hence limited by the speed of light. As the Aerts' model shows, there is yet a third possibility, namely a situation in which correlation is potentially present, but only actualized to its full extent by the act of measurement. This creation-discovery view can be applied to the quantum mechanical situation of two entangled photons, and shows that in the debate of understanding 'what is really going on in Aspects experiments' an alternative explanation can be found, in which potentiality, creation and discovery play a central role.

Keywords Quantum mechanics · Separability · Creation-discovery view

1 Introduction

In his 1981 Doctoral Dissertation Diederik Aerts proposed a general theory for physical systems where quantum systems and classical systems are special cases on the extremes of a spectrum of ways quantum properties and classical properties can combine for a physical system [2, 3]. During the eighties these formal results within Operational Quantum Logic (OQL) [15, 17] became one of the building blocks for an original interpretation of quantum

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mechanics (QM) called the Creation Discovery View (CDV) [6, 7]. The reason we concentrate on the CDV and the way it has dealt with results from OQL is that it is the only interpretation of QM that gives a central role to the fact that quantum systems can be non-spatial. Our paper will deal with a specific characteristic of the non-spatiality of quantum systems, namely the different types of correlation which can occur in entangled systems.

According to the CDV quantum propositional structures can appear in the macroscopical world as well. One way to show this was by devising macroscopical models that reproduce phenomena typical for quantum systems (superposition, non-separability). This idea is part of but does not exhaust the CDV: CDV presents elements of a complete epistemology and metaphysics based on a general approach to physics which grew out of OQL [5, 8, 9]. Following a meditation on the possibility of contributing to CDV from the point of view of mainly analytical philosophy of science one of the present authors tried to argue for the existence of quantum phenomena in the macroscopical world by embedding CDV within a general ontology of so-called pure processes [12–14]. Pure processes are characterized by quantum-like properties. From this ontology, stable, self-identical objects are special cases of pure processes. Phenomena usually restricted to the quantum world become ubiquitous. Aerts' notion of separability, first introduced in [2], is important here because it allows to describe the non-separability of entities without reference to space-time. For example, it can be applied to entities which are not particulars in the sense of classical physics.

In Sect. 1 we give an overview of some basic ideas of CDV and show that CDV is both an epistemology and a metaphysics that wants to replace the classical scientific worldview we inherited from the 19th century. We continue with a discussion of Aerts' concept of separability in Sect. 2, and present the vessels of water model in Sect. 3. In Sect. 4 we present a consideration on the role of potentiality and the creation-discovery aspects of correlations in space-like non-separable quantum experiments. Finally, in Sect. 5, we draw some general conclusions.

2 The Creation Discovery View

The CDV is an interpretation of QM. As any of the hypotheses about the meaning of QM it has an epistemological side and an metaphysical side. In this first section we will take a brief look at both CDV-epistemology and CDV-metaphysics. The scientific worldview we inherited from the 19th century had a metaphysical component and an epistemological component. The metaphysics says that reality is material. A key property of material entities is that they can be uniquely and unambiguously spatially located. The epistemological component says that science describes reality as *it is in itself*. On the whole one can refer to this materialist realism simply as realism.

Realism has been questioned many times, by transcendental idealism, logical positivism, and more recently by post-modernism. However, none of these really tainted the realist status of physics because they are basically of a philosophical nature: they do not come from physics itself. QM is a challenge to realism because it does come from within physics itself. It is not just any theory, but one of the key theories of contemporary physics. The problem QM poses has to do with the existence of superposition states and the way measurements can be understood. In classical physics (CP) (and the realist worldview) we have what we could call causal closure: the physicist can be described by the models of CP, philosophically: the physicist is part of the physical world and his actions can be described entirely in material terms. In QM this has become fundamentally problematic.

More importantly QM poses a challenge to the idea that material entities can be defined in terms of the key property of spatiality because of the possibility of superposition states for the position variable. Basically we can construe the description offered to us by QM quite literally: *quantum entities can be non-spatial*. Moreover, in a quantum measurement there is an element of *creation of properties* during the measurement and because of the measurement, instead of simply a *discovery of properties* that were already there before the measurement. Creation is not controlled by us, but we bring it about and thus it depends on us. Discovery is controlled but, at the same time, independent of us. There are two possible reactions to the paradox of measurement. (1) Idealism. Since we cannot distinguish between the entity and the manner in which we perceive the entity we simply give up causal closure. This is the Bohr-Wheeler view: the measurement situation is essential to attribute a property to a physical system, human decision 'enters the equation'. (2) Realism. We do not give up on causal closure, we remain committed to realism. This is the view Einstein took (for more details we refer to [6, 7]).

Aerts' solution to the realism problem looks for a middle ground between these two extremes, as follows. First, the situation with measurement in the case of the quantum system is generalized to all measurements in physics. More specifically, every measurement has two aspects: a discovery-aspect (as in CP) and a creation-aspect (as one can encounter in QM). In other words, every measurement has an idealistic and a realistic aspect. In fact there is a spectrum of possibilities with pure classical measurements with zero creation on one end of the spectrum, and quantumlike measurements on the other side of the spectrum with maximum creation. Secondly, this Creation Discovery View can be applied, according to Aerts, to other layers of reality as well, e.g. all human interactions have a discovery and a creation aspect. For example suppose I have never thought about state subsidies for mosques in Europe, and somebody asks me if I am for or against: while I was neither for or against beforehand, I choose a position during the 'measurement'. From this one can conclude that many aspects of social phenomena and especially phenomena of consciousness structurally resemble the phenomena of QM. If QM really is non-spatial, the classical (spatial) world is just an aspect of a larger non-spatial reality. Classical reality is just a local contraction in a much larger quantum or quantumlike reality. Aerts has worked out recently a much more concrete explanatory framework for quantum mechanics along these lines, where indeed 'material-energetic-reality' is put forward as a special case of a wider quantum and non material-energetic reality, and such that plausible arguments are given for 'why this could be the case' [10, 11].

3 Aerts' Notion of Separability

In [2] Aerts provided a procedure for treating separated systems within OQL and proved a theorem which states that quantum mechanics cannot describe two separated entities. Together with Piron's representation theorem for quantum logic in Hilbert space [16], this is a key result in quantum logic.

Let us consider two entities S_1 and S_2, with property lattices $\mathcal{L}_1$ and $\mathcal{L}_2$, and sets of states Σ_1 and Σ_2 respectively. For the joint entity S consisting of these two entities, we have the property lattice $\mathcal{L}$ and set of states Σ. Understood in an intuitive way, S_1 and S_2 will be considered as separated entities if, for tests α_1 of S_1 and α_2 of S_2, it is possible to perform α_1 and α_2 together on S in such a way that the outcome obtained for the test α_1 is not influenced by the performance of α_2 and vice-versa. Rigorous definitions are given of what is meant for 'performed together' and 'influence'. We will reproduce the principal definitions and results in the following.

We say that two tests α and β on the entity S are said that can be *performed together* iff there exists an experiment $E(\alpha, \beta)$ having four outcomes, labeled by $\{yes, yes\}$, $\{yes, no\}$, $\{no, yes\}$ and $\{no, no\}$ and such that:

1. α is true iff we are certain to get one of the outcomes $\{yes, yes\}$ or $\{yes, no\}$ for the experiment E.
2. $\alpha^{\sim}$ is true iff we are certain to get one of the outcomes $\{no, yes\}$ or $\{no, no\}$ for the experiment E.
3. β is true iff we are certain to get one of the outcomes $\{yes, yes\}$ or $\{no, yes\}$ for the experiment E.
4. $\beta^{\sim}$ is true iff we are certain to get one of the outcomes $\{yes, no\}$ or $\{no, no\}$ for the experiment E.

Two tests α and β of an entity S that can be performed together are *separated* iff, when for an arbitrary state of the entity a is a possible outcome for α and b is a possible outcome for β, then the combination (a, b) is a possible outcome for $E(\alpha, \beta)$. Once these notions are developed, the definition of separated entities is given:

> **Aerts' Separability**: If we have an entity S consisting of two entities S_1 and S_2, then S_1 and S_2 are said to be *separated* iff every test of S_1 is separated from every test of S_2.

It can be shown that if S_1 and S_2 are separated, then every state of S is determined by a state of S_1 and a state of S_2. In this context it is possible to show Aerts' main theorem which states that while the axioms of classical mechanics are compatible with the description of two separated entities, the axioms of quantum mechanics are incompatible with a description of two separated entities [4].

It must be stressed that this notion of separated systems does not make any explicit reference to space–time separation, but is constructed from the tests that can be performed on the systems S_1 and S_2. Within the operational quantum logic approach these tests can be defined in a very general way, which in principle might have nothing to do with the problem of space–time separation.

4 Aerts' Vessels of Water Example

It was supposed in the eighties, that violation of Bell inequalities provided a direct relation to determine quantum systems and it seemed impossible to find examples of systems violating Bell inequalities different from those described by quantum mechanics. However, Aerts [2] was able to build a macroscopic system whose propositional structure shows a violation of Bell inequalities. Accardi [1] had shown that Bell inequalities are equivalent to inequalities characterizing a Kolmogorovian probability model, so the macroscopical system has a non-Kolmogorovian probability model. Therefore the commonly accepted classification of a microworld described by quantum mechanics and a macroworld described by classical physics was challenged. The example provided by Aerts consisted of two vessels of water (see Fig. 1), V_1 and V_2, each one containing 10 liter of water and which are connected by a large tube T, in such a way that water can pass through one vessel to the other. The experiment e_a consists of extracting the water in V_1 using the siphon S_1 and collecting it in the reference vessel R_1. If the water collected in R_1 overpasses ten liters, the outcome is said to be 'yes', and otherwise, it is said to be 'no'. A totally analogous experiment e_b is performed on V_2. e_{ab} is the coincidence experiment which consists of performing e_a and

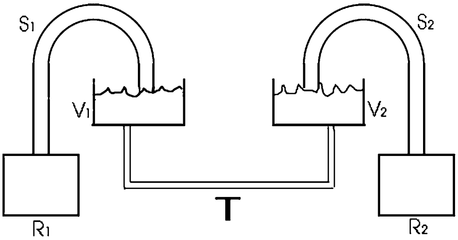

Fig. 1 Two vessels of water, V_1 and V_2, are connected by a large tube T. The water contained in V_1 and V_2 is extracted by the siphons S_1 and S_2, and it is deposited in the reference vessels R_1 and R_2

e_b together [5]. This coincidence experiment shows correlations because of the large tube connecting the vessels. The experiment e_{ab} finishes when water stops flowing in both sides. In order to calculate Bell inequalities, two more experiments have to be introduced. $e_{a'}$ and $e_{b'}$ (exerted on V_1 and V_2 respectively), consists of taking one liter of water from each vessel and checking wether it is transparent. If the extracted water is transparent, the outcome 'yes' is given, and otherwise, the outcome 'no' is given. Then, coincidence experiments $e_{a'b}$, $e_{ab'}$ and $e_{a'b'}$ are defined.

The random variable E_a is defined in such a way that it yields 1 if e_a gives the outcome 'yes', and it yields -1 if e_a gives the outcome 'no'. E_b, $E_{a'}$ and $E_{b'}$ are defined in a totally analogous way. For the coincidence experiment e_{ab}, the random variable E_{ab} is defined. $E_{ab} = 1$ if e_{ab} gives 'yes-yes' or 'no-no', and $E_{ab} = -1$ if e_{ab} gives 'yes-no' or 'no-yes'. In the same manner are defined $E_{a'b}$, $E_{ab'}$ and $E_{a'b'}$. If the system under study (V_1 and V_2 united through T) is in such state that V_1 and V_2 contain 10 liter of transparent water, then $E_{ab} = -1$, $E_{a'b} = 1$, $E_{ab'} = 1$ and $E_{a'b'} = 1$. Then:

$$|E_{ab'} + E_{a'b'}| + |E_{ab} - E_{a'b}| = 4 \geq 2 \tag{1}$$

Thus, this macroscopical system seen from the context of the OQL approach provides a violation of Bell inequalities.

5 States of Potentiality and the 'Creation-Discovery of Correlations'

The violation of Bell inequalities in the vessels of water model presents apparent differences with the case the photons/electrons in the singlet state. However, as we will make explicit below, the vessels of water example gives rise to a possible new interpretation of what happens when a violation of Bell inequalities takes place in quantum mechanics. Besides the differences, an important feature of the Bell violation is its algebraic content. The OQL approach shows us the similarities at this level and allows us to exploit the analogy between the Aerts model and an entangled quantum state. From this perspective, we can focus on what the vessels model can learn us about the nature of quantum entanglement rather than focussing on the differences with the physical situation of two entangled photons (as it is a model, it will and maybe should not reproduce all quantum features, just as spin models can reproduce some of the quantum features of a quantum spin $1/2$, but without dealing with all quantum issues to the fullest details).

Let us note that in the vessels of water model the collapse of the state (or equivalently, the passage of potentiality into actuality) is completed if the two siphons have stopped collecting the water, which defines the end of the measurement process. In an idealized setting this could be done in a perfectly symmetric way with siphons collecting the water in a suitable way. Therefore, even for a classical model (based on fluid dynamics) the measurement collapse could happen ‘symmetric’ over two space-time points which are separated in a space-like sense. If one would make the supposition that to obtain a correlation a signal is necessarily involved which needs to go from one side to the other, then this signal would have to be faster than light. However, from the interpretation of Aerts, in the vessels of water model there is no signal traveling. What happens is that we have partially a correlation which has always been there and stayed detectable while the system (water) was spreading over space (the separated reference/detection vessels), but on the other hand the correlation has also been partially created by the measurement process since we do not know which siphon will poor more water than the other. Following this line of thought one could wonder whether maybe an analogy can be drawn for two entangled photons in the singlet state. One could argue that a similar phenomena as in the vessels of water model occurs, namely that the two photons start as a correlated unity, to the extent that one cannot even call this these ‘two’ photons. It is this photon duality itself which is spin correlated, and it is this type of correlation which stays present until the moment of collapse in the measurement process.

This shows that the vessels of water model could help us to understand quantum entanglement by clarifying the role of potentiality. The discussion presented here motivates us to differentiate between correlations which are (actual) already present (independent of measurement) and those which can only exist through measurement, i.e. they are made actual by the very act of the measurement itself. To clarify this point, let us give the following example, the weather above Paris and Brussels are often found to be correlated. For example, if it rains in Paris there is a high(er) probability that it also rains in Brussels, simply because these regions are (more or less) in the same continental weather situation. Vice versa, if we have cold weather in Brussels then there is a high(er) probability that the same holds in Paris. So there is a correlation between the weather conditions in Brussels and Paris (but not between, let’s say, Brussels and Sidney). This does not pose any mystery at all, because this correlation in temperature was already present and was simply observed by the meteorological instruments. So the fact that we can measure this temperature correlation on two places simply corresponds with the fact that this correlation was already there, regardless of measurement. Hence it would also be there, even if no-one bothered to measure the temperature above Paris and Brussels.

If one considers the situation of the vessels of water model, and also the entangled photons, one observes a new type of correlation, which was not identified before. In a classical setting only two types of correlation situations are possible: (i) the correlation already existed and is simply detected by the measurement (so it is also there even without being measured, i.e. it is not created by the measurement); (ii) a correlation which did not exist *yet* before the measurement and which is established by sending a signal from one side to the other, hence it is purely created by sending the correlating signal in the measurement process and in the classical setting such signals are limited by the speed of light. The water model shows that there is a third possibility between these two extremes (i.e. *discovering* an existing correlation versus *creating* a previously non-existing correlation by sending a signal), namely a situation in which the correlation is realized by/during the measurement itself. For the water model, the correlation was only potentially present before the measurement: e.g. the water can be divided in the proportions of 2–18 liters, but also of 7–13 liters, 11–9 liters and so on. The potentiality lies in the fact that all these different divisions, i.e. different ways of establishing a correlation, are possible. Understood in this way the vessels of water model can be considered as giving a good explanation for what happens in a quantum mechanical setting. Indeed, one of the main features of quantum mechanics is the presence of potentiality. It is even so that the mathematical formalism of quantum mechanics, i.e. the vector space structure of Hilbert space, is naturally adapted to describe potentialities, in contrast with classical point-like representations in phase space in which each property is actual (or not), independent of measurement. Hence the quantum formalism reflects perfectly the concept of a correlation which can be potentially present, but which is only made actual by the act of measurement. So if we reconsider the situation of two entangled photons, the vessels of water model gives a good suggestion of what is going on in the case of two photons in the singlet state. This is of course exactly the point of the creation-discovery view discussed above. In the creation-discovery view there is at the same time a discovery of something which was already present and an act of creation leading to correlations which were only present *in potentia*. This shows how one can recover the typical quantum correlation by bringing together the 'creation' aspect with the 'discovery' part in the measurement.

6 Final Remarks

We have presented Aerts' model and argued how this model clarifies a new type of correlation observed in quantum mechanics, i.e. a situation in which a correlation is realized during the measurement process itself. In classical systems correlation either exists by discovering an existing correlation or else by creating a previously non-existing correlation by sending a signal. As the vessels of water model shows, there is a third possibility, between these two extremes, in which there is partially a discovery and a creation of the correlation, which existed potentially. Thus, the analogies between quantum entanglement and the Aerts model revealed under the light of the OQL approach, provides a new interpretational move which emphasizes the role of potentiality and non-spaciality in quantum entanglement.

On the other hand, according to Aerts, 'the water remains *one whole* till it gets separated in two parts of water, and that is when the correlation gets created. It was only potentially present in the state of the water before the measurement'. But the water in the vessels, although non local in some respect, remains a material substance, and hence it is presence 'inside space'. Following Aerts' interpretation, in which quantum entities are 'not being present inside space', it is here that the analogy of the vessels of water model breaks down. It mimics well 'non locality', and even the aspect of non locality necessary for violating Bell inequalities, but the non locality is of a space-time nature. Quantum non locality, following Aerts' interpretation, is not space-like. The 'vessels of water model' would in this sense be difficult to generalize to entail non locality situations of more than two quantum particles, as remarked in [10].

Finally, we want to emphasize two things: first, the significance of Aerts' model as an intuition pump to understand the nature of non-separability in general, and QM non-separability specifically; secondly, our analysis exposes a possible development of the CDV view. If we consider, as it is done in CDV, that quantum systems are non-spatial, one can argue that, a spatial notion of separability is not applicable to them. We consider this the main strength of the CDV because it contributes to understanding the non-spatial nature of the EPR type experiments. The present paper wants to contribute to the work referred to in the beginning of the introduction, i.e., an ontological foundation to CDV (cfr. [12–14]). By clarifying this comparison we believe that one can further elaborate this aspect of the CDV. We believe that it would be interesting to make further formal developments in order to investigate this distinction more deeply, and that it would throw new light on a better understanding of quantum non-separability.

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