Einstein's Local Realism and the Realistic Interpretation of the Wave Function

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1. Realisms

A realist point of view may be held concerning a wide number of different subject matters: for instance, universals, mental entities, middle-size material objects, unobservable objects of theoretical science, reality in general as such, etc. Moreover, current debates in epistemology, metaphysics and philosophy of science, distinguish a variety of theses that can be held on each of these matters as components of a full-blown realist position[1]. At the core of such a position are first of all the two ontological theses, respectively claiming that the facts (or entities, properties, events, etc.) of a given field (a) exist, and (b) their nature and/or their existence is independent of the fact of being known (or thought of, perceived, etc.). These ontological theses are the stronger kind of realist claims, and constitute the core of Platonism if we are talking about universals, of mentalism if we are talking about mental entities, scientific realism if we are talking about unobservable objects of theoretical science, metaphysics if we are talking about reality in general and as such.

Surrounding this core, there are other weaker preliminary theses, which the realist must be able to establish before even getting at arguing for the ontological theses, and which are rejected by well known forms of anti-realism. First of all there is an epistemic thesis, asserting that it is possible for us to have justified beliefs, hence knowledge, concerning the subject matter at hand. Kant, for instance, maintained that we cannot have knowledge about (independent) reality as such; and Van Fraassen[2] argues that we cannot have reasons enough to support our beliefs concerning the non observable entities postulated by scientific theories; and if this were the

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[1] See ALAI, 1994, ch. 1. References to different classifications of realist theses are contained in the appendix to ch.1.

case, we obviously couldn't even begin to argue about their existence or independence.

The outermost and weakest realist theses are the semantic ones, preliminary even to the epistemic thesis[3]: they claim that (a) our language can describe facts of the subject matter at hand, since its terms *refer* to entities (and properties, etc.) of that subject matter, and (b) we do in fact describe the subject matter, in the sense that our statements about it are to be interpreted as descriptions (or at least as ways of expressing the properties of things that are independent from our minds and our science, but that are notwithstanding given in our actual experience) rather than, for instance, as mere computing devices. Point (b) is rejected by *instrumentalists*, such as, for instance, Nicholas Osiander, who claimed[4] that Copernican cosmology was not to be read as a description of the constitution of the heavens, but as an instrument for generating the correct astronomical forecasts. (a) is rejected by *verificationists* of various sorts, such as, for instance, the early logical positivists, Michael Dummett or Hilary Putnam[5]; in various ways, they claim that our language refers to epistemic facts (such as verification conditions), rather than to objective facts (concerning, for instance, mental entities, the unobservable entities of theoretical science, etc.). It is clear that if we cannot even refer to the facts of a given subject matter, there is no question of our being able to entertain justified beliefs about them, let alone of their existing and being independent.

2. The empirical significance of realist claims

The early logical positivists, in particular, held a *verificationist* theory of meaning whereby the cognitive meaning of any sentence was identified with its empirical content, i.e. with the set of experiences that would directly verify or refute it[6]. Accordingly, any factual sentence that was not *completely* defined in empirical terms (i.e., that couldn't be asserted *if and only if* a given set of experiences obtained, thus entertaining a two-ways conditional relation with that set of experiences) was called "metaphysical", and discarded as devoid of meaning (the focus being on *cognitive* meaning, as opposed to emotive or poetical meaning). Clearly enough, the great majority of philosophical sentences, including the ontological theses

[3] For discussion of this subject in quantum-mechanical context see GAROLA, 1992, and 2000.

[4] In the *Introduction* to Kopernikus' *De Revolutionibus*; KOPERNIKUS, 1992.

[5] See for instance Putnam, "Realism and Reason", in PUTNAM, 1978, p.123-140.

[6] For instance, see CARNAP, 1928 and 1932; SCHLICK, 1936.

of realism, were thought to be metaphysical and meaningless. (The status of semantic realist claims, however, was thought to be different, as they did not concern facts, but meaning analysis; epistemic realist claims, in turn, had a mixed status, as they are partly concerned with factual questions, and partly with conceptual analysis)[7].

Eventually, however, verificationism proved unsustainable: not only because it blurred any distinction between metaphysics and other branches of philosophy (for instance, between metaphysical realism and scientific realism); but even more, because it blurred any distinction between metaphysics and science itself. As Carnap[8] and Hempel[9] (themselves prominent logical positivists) soon understood, theoretical terms cannot be *completely* defined in empirical terms: there is no finite set of experiences occurring *if and only if* a given theoretical sentence is assertible; moreover, in general, a given theoretical term cannot be placed in relation to a given set of verifying experiences directly by itself, but only through the mediation of other theoretical terms. Schematically, it is not possible to claim that theoretical property P is present if and only if experiences of the set E obtain, but that

(1) if (but not *only* if) theoretical properties P and Q are present, than experiences of the set E follow,

or that

(2) if (but not *only* if) experiences of the set F obtain, than theoretical properties P and R are present.

The logical positivists, therefore, abandoned their earlier verificationist theory of meaning for a more "liberalized" empirical significance theory of meaning, according to which a sentence was meaningful if endowed of empirical significance, if the one-way conditional relations of kinds (1) and obtained (2).

Furthermore, it must be asked whether the conditional relations ensuring empirical significance must be deductive (certain), or could also be merely probable (inductive or abductive). Induction is a probabilistic inference enlarging the number of possible elements that share a property, whereas abduction is the inference to the attribution of a new property to the same elements[10]. It might seem that since scientific laws are universal sentences, they may imply observation sentences (that are particular sentences), but not the other way round. Precisely for this reason Popper, who

[7] See, for instance, CARNAP, 1934.

[8] In CARNAP, 1936-37 and 1963.

[9] In HEMPEL, 1952.

[10] PEIRCE, 1866 and 1878.

denied any possibility of justifying induction, substituted falsifiability to verifiability as a criterion of empirical significance: a law could be deductively falsified (by *modus tollens*) on the basis of an observation contradicting it, but not the other way round : it could not be deductively or inductively verified[11].

However, it has been shown convincingly (among others by Duhem[12] and Quine[13]) that any theoretical sentence deductively implies an observation sentence only when the truth of an in principle infinite number of theoretical and observable sentences (stating the obtaining of suitable collateral conditions) is given, and *vice versa*. Peirce said that, if humanity had an eternity at its disposal, humans would converge toward the same truths. Therefore, a sentence should be considered empirically significant even if it entertains merely *inductive or abductive* conditional relations of types (1) and (2) with experience.

In the light of these conclusions, many, if not all, philosophical theses, including metaphysical theses, should be considered endowed with empirical significance; and as far as we are concerned, this is true of many forms of realism, in particular of ontological realism. For instance, it is a probable consequence of the various experiences resulting from tests of scientific theories that the unobservable objects postulated by those theories exist; and it is a consequence of what microphysics tells about electrons that we will observe such and results when performing such and such tests. Hence, the scientific realist claims about unobservable entities are empirically significant. Furthermore, an inductive connection may be stronger or weaker, as the antecedent makes the consequent more o less probable; hence, there is a *continuum* from claims clearly and strongly connected to experience (hence, endowed with definite empirical significance) to claims with very weak connections to experience (hence, possessing only a very feeble empirical significance). For instance, the empirical content of the dispute whether all of our sensations are generated by a material world or by a Cartesian evil demon seems of very little empirical import: on the one hand, in fact, both claims seem to entail exactly the same experiences, while on the other hand it is hard to see how the probability of each of them might be assessed, given the experiences we actually have.

[11] See POPPER, 1959, ch.1.
[12] DUHEM, 1906.
[13] QUINE, 1951.

3. The science / philosophy distinction

The logical positivists thought that philosophy was distinguished from science because the latter but not the former was empirically significant. But if many or most philosophical theses are endowed with (greater or lesser) empirical significance, as we claimed, one may wonder where the distinction between the two fields lie. A partial answer is that the distinction is a gradual one, so that the stronger is a given claim's empirical significance, the more it is science-like, and the weaker its empirical significance is, the more it is philosophy-like. Thus, we may save the logical positivists' intuition that the distinction is based on empirical content, while also accommodating the intuition that there is no sharp distinction among the various fields of knowledge or intellectual enterprise.

This cannot be the whole answer, however, since we quite commonly encounter theoretical conjectures bearing only very weak and unlikely connections to possible experiences, yet squarely belonging to the field of science, not of philosophy: for instance, a newly postulated subatomic particle, whose possible empirical effects are extremely conjectural and highly debatable; a further actual example is the whole string theory. The distinction between science and philosophy, therefore, must *also* take into account other factors. Although it is not easy to exactly circumscribe these additional criteria, it certainly seems to make an important difference whether the strength of the conditional connection between the theoretical claims and experience (their degree of probability) can be straightforwardly and unquestionably evaluated, or it is rather questionable and debatable; whether the nature of the putative theoretical entities or facts is clear and agreed upon, or not; whether the problems raised by a new hypothesis emerge from the interior of a given empirical science or not; etc. Within science, questions of this kind are usually straightforwardly answered thanks to the methodological rules and background assumptions of each discipline. On the other hand, questions falling outside the scope of an established discipline, are much more up for debate, and these might be considered typically philosophical questions.

This last additional distinction criterion largely overlaps with Carnap's distinction between internal and external questions[14]; that is to say, between questions internal to a precise disciplinary setup (language, conceptual apparatus, methodological rules, etc.), hence scientific, and questions external to any well established setup, hence foundational, or generally speaking philosophical. The main difference is that Carnap was mainly

[14] In CARNAP, 1950.

concerned with formalized languages of mathematics and logic, or with some ideal formalized reconstruction of the language of empirical sciences, hence he conceived it as a neat yes/no distinction; while in actual science, it is almost never the case that methodological and evaluation criteria, ontological status classifications, etc., are neatly circumscribed. Once again, therefore, we have only a continuous range from the most univocally decidable questions, which represent paradigmatic cases of scientific questions, to those most open to discussion, constituting paradigmatic cases of philosophical questions.

4. Realism debates in Quantum Mechanics: Instrumentalism and Idealism

There are a number of realism debates concerning quantum mechanics, due to problems encountered in embedding the well established patterns of empirical results in physical models sufficiently analogous to previously known mechanisms to be reasonably plausible. Problems of this kind are raised, for instance, by the existence of extremely precise but irreducibly statistical observative laws, and of exceptionless instantaneous correlations between distant events, apparently without a causal connection. The problem in both cases seems to arise from the violation of the most basic and entrenched principle in science and philosophy, that regularities (whether deterministic or statistical) presuppose a cause. Moreover, in quantum mechanics both the corpuscular model and the wave model seem to be necessary, and yet, they also seem mutually incompatible!

The failure to find suitable physical models for such empirical patterns led physicists as Wigner[15] to embrace instrumentalism, claiming that quantum mechanics should not offer a description of microsystems, but only an algorithm for recovering empirical data. Instrumentalism is an extreme form of antirealism, as it rejects one of the weakest and more basic realist theses: the semantic thesis (b) above, that the statements of theories may be understood as descriptions of unobservable reality.

Others[16], in the attempt to find anyway some form of causal explanation, assume that the emergence of well determined properties from systems in state of superposition may be the effect of subjective knowledge, that produces previously inexistent properties. This, of course, amounts to

[15] See references in AULETTA, 2004.
[16] On this point see TAROZZI, 1981 and 1996 and AULETTA, 2004.

giving up the ontological realist claim that objective reality is independent of cognition, i.e., to a sort of *idealism*.

There are two differences between historical forms of idealism and this new idealist position: first, the formers held that *reality in general* is cognition-dependent (it is thus a metaphysical thesis, in the terminology of § 1), while the latter concerns only micro-physical reality (it is then a sort of scientific antirealist thesis, in the terminology of § 1). This may actually represent an objection for this peculiar form of quantum idealism, for if such a startling phenomenon as the dependence of the object on the subject actually happens, it is hard to see how it could hold only for a limited section of reality, rather than for reality in general. A possible answer, however, might hinge on the very peculiar and utterly basic nature of the quantum world.

The second difference, related to the first, is that classical idealism has practically no conditional relations to possible experiences (it is therefore and in our metaphysical thesis both in the logical positivists' terminology), while quantum idealism does have such conditional relations: in fact, it implies and explains (no matter whether plausibly or not) the puzzling empirical data resulting from our physical experience about quantum phenomena.

5. Realism debates in Quantum Mechanics: waves, particles, and properties

While quantum idealists propose a non-physical explanation for the puzzling empirical patterns of quantum mechanics, others tried, and many are still trying (though with little success) to find a physical explanation. Quite naturally, therefore, they look to the pair of basic physical models (among those enough familiar to science to be minimally plausible) that physicists have tried over three centuries to apply to energetic phenomena: the corpuscular model, and the ondulatory model. Proposals to this effect are mainly based either on one of these models, or on some suitable mixture of them. When particles and their properties, or waves and their properties, are postulated as an explanation for empirical data, such existential claims are endowed with empirical significance; yet, it is easy to anticipate that they are to a certain extent philosophy-like, or raise philosophical questions: this is so, once again, both because the explanation they offer is still quite conjectural, (hence their ties to empirical data are weak), and because in order to account for the unusual empirical behaviour of quantum systems they must be assigned a very peculiar nature, unlike that of classical particles or waves, and as such liable to spur a number of philosophical questions.

As particles and waves are just two of the various entities postulated by theoretical science, ontological debates between realism and anti-realism concerning them are not metaphysical (i.e., in the terminology of § 1, concerning reality in general as such), but squarely fall within the borders of debates on scientific realism. In fact, these debates are among those where philosophical and scientific considerations are most closely intertwined; thus, they yield some of the best examples of how philosophical positions and empirical findings may bear strong relevance to each other, as one of us has repeatedly argued in the past[17]. The physicists who took this line interpreted the proposed models in an ontologically realist way (particles, waves, properties, exist, and are independent from the knowing subject); implicitly or explicitly, therefore, they also held the weaker preliminary realist theses concerning their models: that we have reasons to believe them (epistemic realism) and that we may refer to them, and in fact our theories refer to and purportedly describe them (semantic realism, against verificationism and instrumentalism).

6. Wave existential realism

The first physicist who tried to give an ontological meaning to the wave function was de Broglie[18], who interpreted the quantum-mechanical wave function not as a mere mathematical tool for calculating probabilities of measurement events, but rather as referring to a real classical field embedding a classical particle (thus endorsing the whole array of semantic, epistemic and ontological realist theses). A consequence of de Broglie's approach was that there can be situations in which there are both a field and a particle, and situations where there is only a field (the so-called *empty wave*). For instance, let us suppose that a photon encounters a beam splitter in an interferometer; then, we may think that one path is followed by the photon with its field, the other the empty wave. The possibility to detect empty waves as a strong experimental evidence for the existence of an ontological counterpart of the wave function was underlined by Selleri long ago[19]. Selleri's idea was important under two respects: first, because he pointed out that ontological realism definitely had empirical content; second, because by assuming that "not only energy, momentum, charge, and so on" can be observed, but "transition probabilities can be easily observed too", he suggested that "the real wave could then influence the transition rates of the system with which it interacts", thus envisaging further ways to empirically test his proposal[20]. However, no experiment has been able to confirm such a hypothesis, while some have shown that it is rather implausible[21].

David Bohm[22] developed a different approach to the same strategy. His main idea was that, if quantum systems are somehow connected to (or expression of) a classically physical reality, this should be characterized by some "hidden" variables, able both to explain the exotic behaviour of quantum-mechanical systems (in particular the superposition principle and the basic role of probability), and to reduce it to a classically deterministic theory. In order to accomplish this research program, Bohm was led to introduce the new concept of a *quantum potential*, which could account in deterministic terms for the typical interference effects of quantum systems. However, many tests performed in the last thirty years have shown that a local hidden-variable theory is untenable, and this forced Bohm to develop the idea of the quantum potential in strongly non-local terms; this, in turn, led to a final formulation of a theory which was in open contrast with special relativity[23]. Whether this model will be disproved by future experiments is an open question, even if it seems already physically implausible.

Summing up, this strategy for offering a plausible physical model of quantum mechanics involves ontological realism toward particles, properties and waves; however, the most problematic among these claims has proved to be the existence of waves, both because of the puzzling nature and of the scarce or missing empirical evidence for their existence. From a philosophical point of view, therefore, this strategy is most naturally seen as mainly involving an existence claim on waves.

7. Properties independence realism

A different strategy in the search for a physical model was followed by Einstein, with Podolsky and Rosen[24] (henceforth: EPR). EPR claimed[25] that

[17] See TAROZZI, 1988 and 1993.
[18] See DE BROGLIE, 1955 and 1956.
[19] SELLERI, 1969 and 1971. See also TAROZZI, 1985; CROCA, 1987, and HARDY, 1992.

[20] SELLERI, 1971, p. 400. See also SELLERI, 1982.
[21] See WANG *et al.*, 1991; ZOU *et al.*, 1992.
[22] BOHM, 1952.
[23] See BOHM and HILEY, 1993.
[24] EINSTEIN, PODOLSKY, ROSEN, 1935.
[25] In a very plausible way, as even Kant, for instance, did.

the reality of physical entities or properties cannot be postulated on the basis of *a priori* philosophical considerations, but must be found through experiments and measurements. To this end, they though they didn't need a complete definition of 'reality' (which would indeed have raised thorny philosophical questions), but just a "criterion", i.e. "not a necessary, but a sufficient condition" for identifying real elements. The following criterion they considered to be "reasonable":

> (RC) If, without in any way disturbing a system, we can predict with certainty (i.e. with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.

Bohm[26] introduced a further simplification of EPR argument opening the way to the successive experimental tests. He considered two particles in a special state called "singlet state". In this case, the sum of the spins (the spin is the intrinsic magnetic momentum of particles such as electrons) is zero, and the value that can be found by measurement on a particle is always opposite to the value found on the other particle (if one is in spin down, the other one is in spin up, and vice versa).

It is easy to see why EPR claimed, without explicitly arguing for it, that (RC) was reasonable: when EPR speak of the possibility of predicting with certainty which property will be revealed by a measurement taking place at a distant location at the same or at some later instant, they actually mean *predicting on the basis of the result of the measurement on the system at hand*; that is to say, they are actually talking of the invariable correlation of the latter measurement to the former. Now, it seems that there are only three circumstances which may allow such a correlation: either (i) the property measured on the distant system pre-existed and has a common cause with the property we reveal by measuring the system at hand, or (ii) by measuring the first system we can physically (instantaneously) perturb the second system, thereby either creating or modifying the property on the second system, and thus bringing about the result that is then revealed by the measurement, or (iii) our knowledge of the former result can non-physically influence the latter, either creating or modifying the property on the second system, and thus bringing about the result that is then revealed by measurement. But (iii) is what we called *idealism*, or the action of spirit on matter, and it is excluded both from commonsense and by our prevailing metaphysical commitments. On the other hand, (ii) would represent a violation of Einstein's locality (of special relativity). It follows that *if (iv) we actually register a correlation between the distant property and the property of the close-by system, and (ii)(i.e. instant perturbation) does not obtain, then (i) must obtain*: which is exactly what (RC) says.

[26] BOHM, 1951.

However, this consequence could not be inferred if EPR had not assumed a separability principle, according to which distant systems have properties that are independent from each other. What Schrödinger[27] genially understood for the first time, and later experiments have confirmed, is that quantum-mechanical systems can show a new type of correlation-at-a-distance, known as entanglement, which, though not representing a violation of relativity, and therefore without implying any transmission of signals or any form of communication, connects systems in such a way that the result of any measurement performed locally can depend on the result of a measurement performed on a distant system[28].

Thus, there is a fourth possible explanation of correlations at distance, beyond (i) pre-existence (or "hidden variables"), (ii) non-local perturbation and (iii) idealism: (iv) non-separability, i.e. the fact that the properties of quantum systems are not intrinsic, but depend on the relations (and interactions) that any system has or entertains with other systems. This has nothing to do with (iii) idealism: saying that properties are not intrinsic does not mean they are in any way subjective; saying that they depend on the relations with other systems does not mean they depend on the mind. On the contrary, there are very good reasons to suppose that interacting and related quantum systems show this behaviour quite independently from any observation[29].

By further developing Bohm's model, Bell[30] could prove a theorem, which can be formulated as

> A deterministic hidden-variable theory that acknowledges the separability principle must satisfy the Bell inequality. However, the predictions of quantum mechanics violate it.

Bell inequality imposed a specific quantitative bound on the correlations among distant systems. Though there were some initial bugs[31], experiments performed in the last 30 years[32] have shown that this bound is regularly violated by quantum-mechanical systems.

Summing up, quantum systems show correlations-at-a-distance (entanglement) such that, when considering two correlated particles, one of the

[27] SCHRÖDINGER, 1935. A different solution was proposed by BOHR, 1935.
[28] See also AULETTA, 2006.
[29] See JOOS and ZEH, 1985.
[30] BELL, 1964 and 1966.
[31] MARSHALL *et al.*, 1983.
[32] See ASPECT *et al.*, 1982a and 1982b; and KWIAT *et al.*, 1994.

pair, without transmitting a signal and therefore in anyway perturbing the correlated particle, cannot be considered in isolation from the latter. Entanglement is a specific and non-local (that is, independent from the space and time that can "separate" the two particles) *limitation on the possible results* of a measurement, and in particular it implies that, when locally measuring an observable on a particle, the result that we obtain on the other particle by measuring the corresponding observable is *not independent* of this one. The measurement process is a physical interaction, and entanglement is also a phsycal but non-local (and classically unknown) interdependence. There is therefore no reason to consider such a situation in subjective and idealistic terms. What entanglement shows is that quantum system are *a priori* characterized by relational properties, and hence are *mutually* dependent, quite independently of the presence of a possible observer. Only the *local* results of the measurement (the interactional part of the story) seem to depend on the observer, but actually they only depend on the physical interaction among an apparatus, the measured particle and the environment. It is supposed that such interactions happen spontaneously in nature without the participation of any observer and produce exactly the same results as we may find in our laboratories[33]. Physicists without philosophical background and philosophers without physical background tend to mix the concept of relation and interaction with that of subjectivity, but EPR's *Gedankenexperiment* is interesting (among other things) as it allows to distinguish between these two concepts.

8. Another proposal

In the past two paragraphs we reviewed two historical attempts to find physical models for quantum mechanics, and noticed that they stress, respectively, the existence of entities (waves and particles), and the independence of properties; hence, we called them, respectively, "wave existential realism" and "properties independence realism". Given that a "properties independence realism" in the sense of the intrinsicness of the properties of quantum systems is no longer tenable for quantum-mechanical systems, let us consider how things stand with "existence realism". Recently, this idea has been explored by two of us[34], by showing a connection between entanglement and wave-like behaviour in the context of a complementarity experiment[35]. In this case, we connect two completely different issues, characterizing the above reviewed historical attempts: on the one hand, the violation of separability by quantum systems and, on the other hand, the problem of the ontological status of the wave function, by suggesting that quantum waves represent a non-classical form of reality. In other words, there are reasons to assign an ontological reality to the state of a quantum systems (and therefore to its undulatory behaviour). However, this state is intrinsically characterized by entanglement, and therefore it shows a characteristic non-independence of properties (as we shall see, the probabilities to detect a photon at a couple of detectors are not independent of the probabilities to detect another photon at a second couple of detectors).

If a quantum wave has somehow an ontological reality, then, as already suggested by Selleri, one should be able to obtain predictions that are different from those a corpuscular behaviour would license. Obviously, this must happen by satisfying the complementarity principle. Thus, we came up with the idea of a complementarity situation where such different effects should be observed. Let us consider a couple of photons produced by a non-linear crystal. Initially, the state of the two photons is factorised (non-entangled). Any photon can be detected either by two "early" detectors (D1 and D2), which are placed after a short path, or by two "late" detectors (D3 and D4), located after a longer path. By discarding all the hits in which both photons are detected either by D1 or by D2, we obtain a characteristic entanglement between detection at D1 and detection at D4 and between detection ad D2 and detection at D3: after a photon has been captured by D1, the other photon is prevented by negative interference to reach D3 and forced by constructive interference to reach D4 (and *vice versa* when the first photon is captured by B2).

Truly enough, in this case we won't be able to tell which photon has gone where and through which path, so that there will be no empirical warrant for a realist claim on photons *qua* particles. On the other hand, if, by changing the disposition of the mirrors, we try to know the path, quantum mechanics itself predicts that any of the later detectors (D3 or D4) will click randomly, for obviously no interference will take place; however, once either later detector has clicked, we will be able to reconstruct which electron has gone on which detector through which path, thus empirically warranting our talk of photons *qua* particles.

Now, if when we have a wave-like behaviour we can predict something (the clicking detector) new and different from what the corpuscular behaviour allows to predict (the path), we have good empirical reasons for attributing an ontological reality to the wave and not only to the particle. In other words, we have associated to the wave-like behaviour properties that are empirically testable, exactly those depending on entanglement. We could express the same point by saying that, in the context of a comple-

[33] See ZUREK, 1981 and 1982; also parts IV and V of AULETTA, 2000.
[34] AULETTA and TAROZZI, 2004a and 2004b.
[35] See BOHR, 1928.

mentarity experiment, entanglement is associated to the wave-like behaviour.

Nonetheless, our claim still keeps a distinctly philosophical character: it is obviously very difficult to understand what type of reality waves have[36]. Actually, it is clear that they cannot have the same form of reality as events or particles have. These are well-localized and their properties can be directly measured. On the contrary, it is intrinsically impossible to directly measure quantum waves or states[37]. The existence of such things can only be inferred.

However, this weakness is also a strength of our position : it allows for the first time to connect the claims that an entity exists and that its properties are non-intrinsic. In fact, as we have seen, the wave-like properties of the two photons strongly depend on the experimental context. This means that the ultimate reason why it is impossible to directly catch the reality of the wave is that this reality is intrinsically relational and interactional. One may think that also the corpuscular reality is. To a certain extent this is true, since in a complementary experiment what we detect depends on the way we arrange our apparatus. However, the detection act itself is by definition a detection of a particle (and this result can also be stored and communicated), and this explains the ontological asymmetry between detection events and relational wave-like entities. One may wonder whether there are other reasons for attributing ontological reality to the wave. The most strong reason is that between the wave-like behaviour and the corpuscular behaviour there is a continuum of possible cases[38].

We stress that this experiment has never been performed, yet; thus, we cannot altogether exclude that it could yield the opposite result, however improbable this may be: it might happen that, in spite of the wave-like arrangement, both D3 or D4 clicked randomly, no matter whether D1 or D2 had clicked. In this case, wave realism would be falsified, but *quantum mechanics would be falsified, too*! This, of course, would be a quite startling result, first of all, because the best confirmed physical theory of all times would be disconfirmed.

A surprising feature of such a possible outcome is that a philosophical hypothesis would be empirically falsified. While this was considered to be impossible by the logical positivists and Popper alike, it would no longer be so surprising after our meta-scientific and meta-philosophic conclusions

[36] One of the first physicists to raise the problem was HEISENBERG, 1958. See AULETTA, TAROZZI, 1994a.

at §§ 2, 3; yet, it would still be a significant illustration and confirmation of those conclusions. One might suggest that the unexpected experimental result would not so much falsify a philosophical hypothesis, as shift it from the more philosophy-like to the more science-like section of the spectrum, by suddenly transforming a quasi-mental experiment into an actual experiment; still, we would have the case of a philosophical hypothesis so sensitive to empirical findings to lose (if not its truth-value) at least its philosophical character. Once again, we would notice that the border between philosophy and science is so permeable, that hypotheses may cross it. Popper had already noticed[39] that a philosophical tenet (such as, e.g., atomism) can become scientific, by becoming *falsifiable*; but we are now seeing that it can become scientific also by *being falsified* (which Popper considered to be impossible, since a claim cannot be falsified unless it is falsifiable, and philosophical claims were precisely non falsifiable, in his view).

A further noticeable consequence of a negative result of our proposed experiment would be the overturning of a very well established physical theory (quantum mechanics) through a philosophical discussion, more or less as Mach's instrumentalism and phenomenism led to the operationist treatment of time in Einstein's special relativity paper that (exactly a century ago!) overturned Newtonian mechanics. Once again, of course, nothing of this kind could ever happen if science and philosophy were divided by sharp and impassable barriers.

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