Renninger’s Thought Experiment: Implications for Quantum Ontology and for Quantum Mechanics’ Interpretation

W. De Baere

Unit for Subatomic and Radiation Physics, Laboratory for Theoretical Physics, State University of Ghent, Proeftuinstraat 86, B–9000 Ghent, Belgium

It is argued that the conclusions obtained by Renninger (Z. Physik 136, 251 (1953)), by means of an interferometer thought experiment, have important implications for a number of still ongoing discussions about quantum mechanics (QM). To these belong the ontology underlying QM, Bohr’s complementarity principle, the significance of QM’s wave function, the “elements of reality” introduced by Einstein, Podolsky and Rosen (EPR), and Bohm’s version of QM (BQM). A slightly extended setup is used to make a physical prediction at variance with the mathematical prediction of QM. An English translation of Renninger’s paper, which was originally published in German language, follows the present paper. This should facilitate access to that remarkable, apparently overlooked and forgotten, paper.

PACS numbers: 03.65.-W, 03.65.Bz
Keywords: quantum ontology, quantum mechanics, interpretation

I. SOME HISTORICAL NOTES

Some 80 years ago the main equations of QM have been invented, with a subsequent overwhelming success of its predictive power, see e.g. M. Jammer [1]. In contrast, however, its significance or interpretation is still the subject of intense debate. These interpretations range between two possible extremes. One extreme contains the Copenhagen–like interpretations [2], to the other extreme belong the “realistic” interpretations. Whereas the former are concerned mainly with relationships between measurement outcomes and carefully avoid ontological statements, the latter consider observations made by human observers as properties possessed by real existing objects. Each of these interpretations has its range of supporters, and each claims to give a acceptable explanation of what QM is really about.

An extensive historical survey is given in M. Jammer’s classic book “The Philosophy of Quantum Mechanics – The Interpretations of Quantum Mechanics in Historical Perspective” [3]. However, in the literature the question is rarely addressed whether there exist empirical data or thought experiments which could rule out some of these interpretations. More precisely, the issue is whether there exist unavoidable ontological truths which should, therefore, be part of any acceptable interpretation. The answer – maybe unexpected and surprisingly – is that such a truth exists. Indeed, in 1953 M. Renninger published a paper “Zum Wellen–Korpuskel–Dualismus” (“On Wave–Particle Duality”) in Zeitschrift für Physik [4] in which an interferometer thought experiment played a central role. The basic result of Renninger was that, independently of any theory, physical reality at the quantum level exists of extended objects which at the same time, i.e. in the same experiment, have a wavelike and a particle-like behaviour. Because this conclusion rests purely on empirical facts, Renninger argues that it is compelling and unavoidable. It should, therefore, be part of any reasonable interpretation of QM. Yet even today, more than 50 years after Renninger’s paper, this is not the case. How can this be, how is it possible that such a
fundamental truth has been overlooked and apparently completely forgotten? One exception is M. Jammer’s book \[3\] where Renninger’s paper is mentioned (p. 494), together with some reactions by A. Einstein, M. Born, and P. Jordan. According to M. Jammer it “caused quite a stir” among the experts in quantum physics.

It is interesting to recall that this picture of physical reality was already introduced by L. de Broglie as early as the introduction of the quantum formalism. It was supported by e.g. A. Einstein and E. Schrödinger, and later on used by D. Bohm in his attempt to set up an alternative formulation of QM. For this reason we will call this model the de Broglie–Einstein–Bohm (dBEB) model. So, basically it was L. de Broglie who introduced the idea that in reality, a quantum system should be considered as an extended structure having at the same time wave–like and particle–like properties. These particle–like properties should then be characteristics of a more localized region within the extended phenomenon. In the dBEB model, in some way the localized region – or the “particle” – is guided by the more extended structure. In Bohm’s version of QM, a so–called “quantum potential” is introduced to do this job. Now, again invoking Renninger’s ingenious analysis, the idea of such a guidance is supported convincingly when the extended structure moves through a system, such as a Mach–Zehnder interferometer (MZI). Indeed, depending on the wave properties of (various components of) that structure as it moves through MZI, the subsequent observation may occur in one of physically separated detectors, and is the result of the interference of different real waves (see Section 2).

From the lack of referring to Renninger’s paper in later, more recent, works on the interpretation of QM and, in particular, on the “reality of quantum waves”, it may be concluded that this work has been unnoticed entirely by the English and the French speaking physics community. Indeed, it is never cited, neither by e.g. de Broglie when – after early criticism by W. Pauli – he took up again his idea, nor by Bohm while developing (together with J.P. Vigier) his alternative approach to QM, which was precisely based on de Broglie’s model of a quantum system. As a result, the fundamental importance of Renninger’s conclusions – the existence of a causally influencable ontological reality, in particular of the reality of the so–called “empty wave” (EW) – have been overlooked and forgotten also by present day physicists working in the field of the foundations of QM. However, as the present author is convinced of the fundamental importance of Renninger’s penetrating analysis of wave–particle duality underlying QM, an English translation has been made of the original German version. It is hoped that in this way many investigators in the field of the foundations of QM may reconsider or revisit their ideas with respect to quantum ontology, the significance of the quantum formalism, and other related quantum issues (see also Section 3).

More recently, the following investigations were carried through to prove the reality of EWS in the sense of observably influencing other physical systems. First, from 1980 on, there were studies by Selleri \[5, 6, 7\], Croca \[8\] and others \[9\]. In some of these proposals it was maintained that there was an observable difference between QM and a theory based from the outset on the dBEB model of reality. However, experimental results obtained by L. Mandel and coworkers \[10\], “...clearly contradict what is expected on the basis of the de Broglie guided–wave theory, but are in good agreement with the predictions of standard quantum theory...”. In a subsequent comment, P. Holland and J.–P. Vigier \[11\] replied that Mandel’s results did not invalidate the dBEB model of reality itself. Finally, more recently there was an attempt by L. Hardy \[12\] to prove the observable reality of EWS, which was criticized in various papers \[13, 14, 15, 16\], followed by replies by Hardy \[17, 18\].

The purpose of the present paper is threefold. First, in Section 2 we recall the basic results obtained by M. Renninger already in 1953 \[4\] about the ontology underlying QM, and emphasize the unavoidable character of Renninger’s conclusions. Next, in Section 3, we give a brief survey of the implications for some present day quantum issues. Finally, by considering an alternative setup in Section 4, we extend and
complete Renninger’s argumentation by showing that empty waves not only are causally influencable (as proven in [4]), but are themselves able to influence observably other physical systems. The main difference with Hardy’s argumentation is that we get our conclusion without the introduction of any specific supplementary hypothesis in order to ascertain the path along which the “particle” possibly moves.

II. RENNINGER’S ARGUMENTATION: MAIN RESULTS

Renninger’s setup is essentially a Mach–Zehnder interferometer which we present here as in Fig. 1, in which the same notations as in Renninger’s original work are used.

A source in path 1 prepares single quantum systems $S$ (photons in [4]) which move towards a losses 50–50 beam splitter situated in a location 2. From location 2, two paths lead to mirrors $S_A, S_B$, who reflect the beams in path 6 and 7 to a second beam splitter in location 3. Finally, detectors $D_1, D_2$ are located in outgoing paths 4, 5. As a first essential point, Renninger remarks that in his argumentation only empirical facts are considered, and that, hence, his conclusions are independent of any existing theory used to explain these empirical facts. The empirical facts considered by Renninger are then the following ones:

a. If detectors are placed in paths 6-8 or 7-9, then detection will occur in only one path at the same time, never in both together.

This proves the particle-like aspect of the phenomenon of the passage of the quantum system through MZI.

b. For equal path lenghts 6-8 and 7-9, with each single quantum system moving through MZI, there will correspond an observation with certainty in $D_1$, while nothing will be observed in $D_2$.

This may be interpreted as the result of interference of waves simultaneously moving along paths 6–8 and 7–9, and should be considered as evidence for the wave-like aspect of the phenomenon in the same setup.

This has been verified by Grangier et al. [13] for light.

c. If a transparent “half–wave” plate is inserted at a specific location in one of the paths 6-8 or 7-9 at appropriate times (i.e. before the system $S$ has passed that location), then observation behind a beam splitter at 3, will now occur with certainty in detector $D_2$.

The fact that it does not matter in which path the half–wave plate is inserted, is according to Renninger empirical evidence for the simultaneous motion – or existence – of physical realities in both paths. Because of a. above, Renninger speaks of an “empty wave” moving along one path, and of another wave containing the “particle” along the other path. In order to distinguish furtheron both waves, we will call this wave the “full wave” (FW), i.e. the one responsible for transfer of particle–like properties. If necessary, we will add an index $S$, e.g. EWS, FW$S$.

d. The result of the action in c., i.e. steering detection from $D_1$ to $D_2$, may be suspended by inserting on a later instant another – or even the same! – half–wave plate in the same or in the other path. And, if the paths are long enough, then the previous action may be repeated an arbitrary number of
times, each time in such a way that it will be *causally predictable*, i.e. with certainty, in which detector $D_1$ or $D_2$ observation will take place.

This is further evidence for the reality of both EW and FW.

For the subtleties of the argumentation, we refer to Renninger’s paper [4] or to its translation in English.

III. IMPLICATIONS FOR VARIOUS ISSUES IN QUANTUM MECHANICS

A. The nature of quantum systems

It follows from Renninger’s thought experiment that ontologically a quantum system is an extended structure consisting of realities which, under appropriate circumstances (such as after the passage through a beam splitter), may move along paths largely separated in space. Hence, in considering physical processes it is reasonable to make the hypothesis that, ultimately, it are the properties of the *entire* structure that brings about a definite localized measurement outcome. One such property is, e.g., the phase difference between $EW_S$ and $FW_S$.

What Renninger has shown also is that, in one and the same single experiment, both $EW_S$ and $FW_S$ may be influenced *in a causal way* by placing another system $S'$, in particular $FW_{\lambda/2}$, in either path 6–8 or 7–9. Here the causal character of the influence refers to the certainty of predictions about observations after a subsequent interaction with the second beam splitter in the location 3.

Also, it might be the case that both ontological components of a quantum system $S$ – i.e. $EW_S$ and $FW_S$ – may be influenced either separately or both at the same time, again in a causal way in the case of a $\lambda/2$–system. And furthermore, the possibility should be envisaged that, conversely, both realities themselves have the ability to influence observably the realities of other physical systems. In particular this would imply that $EW_{S'}$ associated with one system $S'$ should be able to influence $EW_S$ associated with another system $S$, changing in this way the wave guiding $S$, which finally gives rise to a localized observation. This possibility is discussed in Section 4.

So, Renninger’s thought experiment has revealed that ontologically – and independent of any physical theory – quantum systems should be considered *at the same time* as consisting of an *extended structure* with wavelike properties, *and* a more localized region within this structure which is able to exchange with other systems, properties which are characterized by means of particle–like variables such as energy $E$, momentum $p$, spin, etc. Basically, Renninger’s work confirms – on empirical grounds – the validity of the dBEB picture of physical reality.

B. Bohr’s complementarity

According to Bohr’s complementarity principle, the behaviour of a quantum system in a particular process is either wave–like or particle–like. In essence, it is the whole setup, including the measurement apparatus, which determines whether a quantum system behaves as a particle or as a wave, but never in both ways together. However, Renninger’s interferometer thought experiment clearly shows that the passage of *one single* quantum system through the simplest version of a MZI reveals both aspects at the same time: a detector placed in either of the paths 6–8 or 7–9 reveals its particle–like behaviour, while the causal effect of the insertion of a $\lambda/2$ plate in either path – and the subsequent observation in either $D_1$ or $D_2$ – should be interpreted as evidence of its wave–like behaviour.

It is interesting to note here that Renninger’s empirically based conclusion predates by 40 years similar conclusions obtained by e.g. Ghose and D. Home [20, 21].

C. The significance of the wave function

Like EPR, it was not Renninger’s aim to criticize QM, but only “... to point to some very precise conclusions, which follow merely from purely experimental physical aspects, without any pre-
vious knowledge of the mathematical quantum formalism...”. Once these conclusions have arrived at, Renninger is, however, very clear about the significance of QM’s mathematical formalism: “Of course one is free, to speak of the wave as a pure “probability”–wave. But one should be aware of the fact, that this probability wave propagates in space and time in a continuous way, and in a way that she can be influenced in a finite region of space – and only there! – and also at that time! –, with an unambiguous observable physical effect!”

So, by Renninger’s result the meaning of the QM wavefunction \( \psi \) is very clear, both ontologically and mathematically: ontologically \( \psi \) represents a real, causally influenceable wave, and mathematically it satisfies the deterministic Schrödinger equation. The important significance of Renninger’s analysis is to have revealed, in a compelling and unavoidable way, the existence of a deeper lying layer of reality, the causal and quantitative behaviour of which is mathematically described by the standard quantum formalism. Therefore, it is fair to say that Renninger’s results should be part of any acceptable interpretation of QM, and that it is unreasonable to discard quantum ontology, and look at QM only in a pure mathematical way. Hence, it is incorrect to claim that the meaning of \( \psi \) is nothing more than a mathematical function which enables one to predict future statistical results for given initial conditions. Yet, this viewpoint has been defended from the early days of QM (e.g. by advocates of Bohr, Heisenberg and others), thereby neglecting Renninger’s findings, right up to now (see e.g. the provocative paper by Peres and Fuchs, “Quantum theory needs no ‘Interpretation’” [22], probably because of being innocent of Renninger’s basic work.

Therefore, I think that Renninger’s conclusions answer many of today’s issues with respect to the significance of the wave function. And, had the significance of Renninger’s work been appreciated properly in past and recent times, it would have influenced significantly many other papers. In fact, the overwhelming amount of relevant literature should have reduced considerably. Therefore, it is pointless to make a selection from among the huge list of available references – anyone should make his own selection, and judge in what sense the papers’ statements should be adjusted by taking into account Renninger’s 1953 analysis.

D. The issue of Einstein locality

In his paper Renninger strongly argues in favour of the validity of the locality principle (“Einstein locality”) underlying Einstein’s successful relativity theories. In his discussion on a possible alternative for the ontological reality of the EW, he states that the only alternative for explaining the wavelike behaviour of a quantum system, e.g. in a MZI setup, would be the introduction of a “normal electromagnetic wave” with the unavoidable consequence that “…at the moment of absorption the wave would contract with superluminal speed, and moreover through closed walls. Such assumption would be completely unacceptable” [emphasis by the present author]. Of course, at present one could object that Renninger’s analysis predates about one decade Bell’s investigations [23] of the EPR issue, and that according to the present majority view, Bell’s theorem “proves” a nonlocality property of QM. However, in recent and past work (see e.g. [24]) we have argued strongly in favour of the validity of Einstein locality, and concluded that the breakdown of counterfactual definiteness at the level of individual quantum processes would be a far more reasonable explanation for the violation of Bell’s inequality by QM, and for resolving all other so-called contradictory results.

E. EPR’s elements of physical reality

In his paper, Renninger also reports about Einstein’s interest in his analysis. In particular, EPR’s notion of “elements of physical reality” is mentioned as having inspired Renninger’s own definition of “physical reality” (see the Abstract of [4]): “The notion ‘physical reality’ should be understood such that, when this physical reality is considered in a particular space at a particu-
lar time, it should be experimentally possible to influence this reality in such a way that future results of experiments show unambiguously that this reality has been causally influenced by the experimental act in this space and at that time.”

Here one may remark that, as in the EPR paper, Einstein, there is a clear relationship between predictions for later observations in some detector, and formerly existing, causally influenceable, realities. Because of this relationship one may identify Renninger’s realities with EPR’s definition of “elements of physical reality”. In this sense, the realities corresponding with EWs may be considered as EPR “elements of physical reality”, of which one might reasonably expect, as claimed by EPR, that they have a representation in the physical theory. However, according to Renninger, this is not the case with the present QM formalism: “…the proven reality of the wave associated with the single particle, which quantum mechanics, …, is unable to account for …”.

IV. ON BOHM’S VERSION OF QUANTUM MECHANICS

Because Renninger’s analysis confirms on empirical grounds the dBEB picture of reality at the quantum level, one might be tempted to conclude that Bohm’s reformulation of QM in terms of the notion of “quantum potential” supersedes the standard quantum formalism. However, one of Bohm’s intentions was to present a causal quantitative formalism for the description of single quantum processes, and to get back immediately – almost by construction – the statistical predictions of QM.

As is well known, the price to be paid was that the quantum potential should be interpreted as resulting from an instantaneous action–at–a–distance between quantum systems, and with an intensity which is independent of the mutual distance between these systems. Here the term “quantum system” should be understood as that localized part of the extended structure which has the characteristic to exchange particle–like properties such as $E, p$, etc. with other systems.

However, it is precisely because of the conflict between the explicit nonlocality property of Bohm’s quantum potential with the empirical validity of locality in actual physical processes, that BQM cannot be considered as a valid quantitative scheme for individual quantum processes. Recalling that QM in general makes deterministic predictions for the statistics of measurement outcomes, the minimum requirement for any attempt to reproduce these predictions in terms of a local theory for individual processes should be the introduction of extra or supplementary variables in the theory. This means that BQM cannot be considered as such a valid alternative HVT for QM. At best, it is only a reformulation of QM in terms of another mathematical quantity – the quantum potential – which should be considered only from a mathematical point of view, i.e. it may not be considered as a faithful representation of the underlying physical reality lead bare by Renninger.

Probably, this was one reason for Einstein to consider Bohm’s solution as “too cheap” (see e.g. [26]). Therefore, an acceptable alternative would be a theory based on the dBEB picture in which the validity of locality is retained. However, not only does such a formalism not yet exist, but neither is there any onset to set up such a formalism (see, however, [27]).

V. ANOTHER POSSIBLE PHYSICAL CONSEQUENCE OF THE dBEB PICTURE OF REALITY

A. Physical argumentation

In his work, on page 9, Renninger addresses the following question: “What happens to the wave devoid of energy of a photon after its absorption? When it is absorbed for example in (6), and when in addition the detectors in (4) and (5) are removed, what happens then with the wave in B? Does she move further towards infinity, or does she disappear at the moment of absorption? Of course this question cannot be answered principally. The former assumption appears to be the more natural one, because it avoids the conclusion to the existence of influ-
ences which propagate with infinite speed also through closed walls, a conclusion which within the physical world is inconceivable. In any case were such influences not associated with transport of energy."

Although Renninger is of the opinion that “...this question cannot be answered principally...”, we yet propose a slightly modified setup in which this issue might be clarified. In fact, we follow Renninger’s own proposal that the dBEB model of reality can be used as “a valuable aid for the visual comprehension of elementary processes and for making exact provisions about the outcome of experiments.” Because the modified setup is almost as simple and elementary as Renninger’s setup, we have some confidence about the correctness of our predictions applying to the new setup. These predictions now concern observable effects of the EW reality on other physical systems and, as in Renninger’s analysis, only physical arguments are invoked.

In this section we elaborate on the ontological picture resulting from Renninger’s argumentation. If the behaviour of a quantum system is determined by its ontological constitution – consisting of both wave and particle characteristics – one should be able to influence this behaviour either by changing the wave characteristics, or by changing the particle characteristics. The first possibility has been evidenced by Renninger’s point c. in Section 2, i.e. the insertion of a material system – a half–wave plate – in either path. Hence, in this case it is the component FW\(_{\lambda/2}\) which provokes the observable influence. The question then naturally arises, whether the wavelike properties of the components EW\(_S\) or FW\(_S\) of S may also be influenced by the empty wave component of another system, e.g. the component EW\(_{S'}\) of quantum system S'.

This implies that one should be able to observe the effect of superposing the realities EW\(_{S'}\) with EW\(_S\) or FW\(_S\). To this end we supplement Renninger’s setup in a minimal way by adding 1) another source of systems S', 2) a third beam splitter BS\(_2\) in location 2', and 3) by letting mirror S\(_B\) removable (see Fig. 2).

Systems S' move then along direction 1' towards BS\(_2\). The outgoing arms are A', which is in line with path 9, and B' which contains a detector D\(_2\). For given masses m\(_S\) and m\(_{S'}\) we choose the velocities \(v_S\) and \(v_{S'}\) such that the frequencies of the waves associated with S and with S' are the same. We are now inter-

![FIG. 2: Modified interference set–up](image)
a result of this superposition the wave properties of \( S \), in particular the phase, will have been changed. Then it might legitimately be expected that, as a result of this interaction, the coherence between \( EW_S \) and \( FW_S \) has been disturbed, and that the final superposition of these real waves within \( BS_3 \) will no longer give rise to observations in detector \( D_1 \) only. Observation of \( S \) in \( D_2 \) should then be considered as evidence for the ability of empty waves to influence other physical systems, i.e. either another empty wave or a material system, in a directly observable way. As a final remark, we note that in the above reasoning we have only used Renninger’s conclusion of the reality of empty waves, and supplemented it only by the reasonable assumption that physical realities may be changed by interactions among them.

**B. Quantummechanical predictions**

Let us now look at how QM describes the processes in this minimally extended MZI setup. The systems leaving the sources in paths 1 and 1’ may be assumed independent, and their state is the direct product \(|1⟩|1’⟩\). Passage of \( S’ \) through \( BS_{2’} \) and of \( S \) through \( BS_2 \) results in the evolution:

\[
|1⟩|1⟩ \xrightarrow{BS_{2’}BS_2} \frac{1}{\sqrt{2}}(|A’⟩e^{ik’z_{A’}} + i|B’⟩e^{ik’z_{B’}}) \times \frac{1}{\sqrt{2}}(|A⟩e^{ikz_A} + i|B⟩e^{ikz_B}),
\]

where \(|A⟩\) represents the state along a horizontal path, \(|B⟩\) the state along a vertical path, etc. Now, because we will be interested in observations in \( D_1 \) and \( D_2 \) for equal path lengths 6–8 and 7–9, we may replace already at this stage the lengths \( z_A \) and \( z_B \) by \( z \). In a similar way we replace \( z_{A’} \) and \( z_{B’} \) by \( z’ \). This gives rise to common exponential factors \( e^{ikz} \) and \( e^{ik’z’} \). Reflection at the mirrors amounts to a phase shift of the states by \( \frac{\pi}{2} \), and the QM state transforms further to

\[
\frac{s_As_B}{\sqrt{2}} \left( |A’⟩ + i|B’⟩ \right) e^{ik’z’} \frac{1}{\sqrt{2}} \left( i|B⟩ - |A⟩ \right) e^{ikz},
\]

At this moment, observation in detector \( D_2 \) is recorded, and only those cases where \( S’ \) is observed in \( D_2’ \) are retained. This subensemble is described quantummechanically by the state

\[
|Ψ_{12}⟩ = \frac{1}{2} |A⟩ e^{ik’z} (i|B⟩ - |A⟩) e^{ikz}.
\]

It follows that the systems \( S \) in this subensemble are still described by the QM state

\[
|Ψ_S⟩ = \frac{1}{2} (i|B⟩ - |A⟩) e^{ikz}.
\]

Finally, after the passage through \( BS_3 \), this state becomes again:

\[
|Ψ_S⟩ = i\frac{1}{2} (|B⟩ + i|A⟩) e^{ikz} \xrightarrow{BS_3} \frac{1}{\sqrt{2}} |A⟩ e^{ikz},
\]

so that QM predicts that all systems \( S \) will still be observed in detector \( D_1 \). Clearly this reflects the fact that the QM formalism predicts that EWs cannot influence other quantum systems in an observable way.

So, observations in \( D_2 \) would clearly be caused by the influence of \( EW_{S’} \) on system \( S \) itself. This, then, would be conclusive evidence for the possibility of EWs to influence in an observable way other physical systems.
VI. CONCLUSIONS

In this work we have reviewed Renninger’s penetrating analysis leading to his empirical proof of the reality of quantum waves, in particular of the empty wave. We have argued – or, rather, called attention to Renninger’s opinion – that these results have fundamental ontological significance. If de Broglie should be credited for the idea, then Renninger should certainly be credited for the empirical proof of its validity. We also discussed briefly the impact on some still ongoing issues in the foundations of QM. In particular, the dBEB ontological picture of reality should be part of any acceptable interpretation of QM, implying that many of these interpretations should be revised.

Next, we have proposed a slightly modified setup in which, possibly, the real EW should influence – instead of being influenced by – another quantum system in an observable way. This influence should manifest itself by an observation in detector $D_2$, whereas QM still predicts no observation in that detector.

If it should turn out that QM gives the wrong prediction, then a new formal scheme should be required for giving a more faithful description of the EW reality – a description which QM is unable to give. Tentatively, this could be realized by means of a local HVT having the general characteristics described in [24].

[1] M. Jammer. *The Conceptual Development of Quantum Mechanics*. McGraw–Hill Book Company, New York, 1966.
[2] H.P. Stapp. The Copenhagen Interpretation. *Am. J. Phys.*, 40:1098–1116, 1972.
[3] M. Jammer. *The Philosophy of Quantum Mechanics*. John Wiley & Sons, New York, 1974.
[4] M. Renninger. Zum Wellen–Korpuskel–Dualismus. *Z. Phys.*, 136:251–261, 1953.
[5] F. Selleri. On the direct observability of quantum waves. *Found. Phys.*, 12:1087–1112, 1982.
[6] F. Selleri. Can an actual existence be granted to quantum waves. *Ann. Fond. L. de Broglie*, 7:45–73, 1982.
[7] J.Àndrade e Silva, F. Selleri, and J.-P. Vigier. Some possible experiments on quantum waves. *Lett. Nuovo Cim.*, 36:503–508, 1983.
[8] J.R. Croca. An experiment for detection of empty waves. *Phys. Lett. A*, 124:22–26, 1987.
[9] J.R. Croca, A. Garuccio, V.L. Lepore, and R.N. Moreira. Quantum–optical predictions for an experiment on the de Broglie waves detection. *Found. Phys. Lett.*, 3:557–564, 1990.
[10] L.J. Wang, Z.Y. Zou, and L. Mandel, “Experimental Test of the de Broglie Guided–Wave Theory for Photons”, *Phys. Rev. Lett.* 66, 1111 (1991).
[11] P.R. Holland and J.-P. Vigier. Comment on ‘Experimental Test of the de Broglie Guided–Wave Theory of Photons’. *Phys. Rev. Lett.*, 67:402, 1991.
[12] L. Hardy. On the existence of empty waves in quantum theory. *Phys. Lett. A*, 167:11–16, 1992.
[13] C. Pagonis. Empty wave: not necessarily effective. *Phys. Lett. A*, 169:219–221, 1992.
[14] R.B. Griffiths. Empty waves: a genuine effect? *Phys. Lett. A*, 178:17–21, 1993.
[15] M. Żukowski. “On the existence of empty waves in quantum theory”: a comment. *Phys. Lett. A*, 175:257–258, 1993.
[16] W. De Baere. Does the quantum formalism allow for the observability of empty waves? *Found. Phys. Lett.*, 10:119–130, 1996.
[17] L. Hardy. Reply to ‘Empty waves: not necessarily effective’. *Phys. Lett. A*, 169:222–223, 1992.
[18] L. Hardy. Reply to Żukowski’s comment. *Phys. Lett. A*, 175:259–260, 1993.
[19] P. Grangier, G. Roger, and A. Aspect. Experimental evidence for a photon anticorrelation effect in a beam splitter: a new light on single–photon interferences. *Eur. Phys. Lett.*, 1:173–179, 1986.
[20] P. Ghose and D. Home. Wave–particle duality of single–photon states. *Found. Phys.*, 22:1435–1447, 1993.
[21] P. Ghose and D. Home. The two–prism experiment and wave–particle duality of light. *Found. Phys.*, 26:943–953, 1996.
[22] C. Fuchs and A. Peres. Quantum theory needs no ‘Interpretation’. *Phys. Today*, March 2000:70.
[23] J.S. Bell. On the Einstein Podolsky Rosen paradox. *Physics*, 1:195–200, 1964.
[24] W. De Baere. On the physical consequences of retaining locality in physical theory. *Found. Phys.*, 35:33–, 2005.
[25] P.R. Holland. *The quantum theory of motion*. Cambridge University Press, Cambridge, 1997.
[26] N. Bohr. Discussion with Einstein on Epistemological Problems in Atomic Physics. In P.A. Schilpp, editor, *Albert Einstein: Philosopher–Scientist*, pages 199–241, Evanston, 1949. Library of Living Philosophers. Reprinted in “Quantum Theory and Measurement”, eds. J.A. Wheeler and W.H. Zurek, p. 9.
[27] K. Hess and W. Philipp. Bell’s theorem and the problem of decidability between the views of Einstein and Bohr. *Proc. Nat. Acad. Sci. USA*, 98:14228–14233, 2001.