Popper and the Quantum Controversy

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1 Introduction

It is almost a truism to say that the philosophy of science systematized by Karl Popper (1902–1994) was heavily influenced by the intellectual landscape of physics. Indeed, falsifiability as a criterion to discriminate science from other forms of knowledge was largely indebted to Einstein's predictions drawn from his general theory of relativity. At the same time, Popper's falsificationism left a deep and long-lasting mark on the way physicists perceived their common practice. However, Popper's contribution to the philosophy of quantum physics and its influence among practitioners has been long overlooked and only in recent years has this issue gathered some historiographical attention (Freire 2004; Shields 2012; Howard 2012; Del Santo 2018, 2019, 2020).

Popper's contributions to foundations of quantum mechanics can be divided into three main periods. As early as 1934 he conceived a thought experiment which allowed him to confront the founding fathers of quantum physics such as Albert Einstein, Werner Heisenberg and Niels Bohr. However, this proposal turned out to be mistaken and this accident led Popper away from the quantum controversy for several years.

The second period of Popper's involvement in the debate over quantum foundations spans 1950s–1960s, when he formulated a new interpretation of probability

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and at the same time of quantum mechanics—the propensity interpretation—gathering the support of several important physicists including David Bohm and Louis de Broglie. In particular, at the end of 1960s, Popper published two influential papers—“Quantum Mechanics without the Observer” (Popper 1967; see Del Santo 2019) and “Birkhoff and von Neumann’s interpretation of Quantum Mechanics” (Popper 1968; see Del Santo 2020)—which allowed him to cross the disciplinary borders and become a full-fledged member of the physics community concerned with quantum foundations in the following years.

Finally, in the 1980s, Popper gave another remarkable contribution to foundations of quantum mechanics, publishing a comprehensive volume on *Quantum Theory and the Schism in Physics* (Popper and Bartley 1982). Here he also proposed a new version of the Einstein-Podolsky-Rosen (EPR) thought experiment alleged to put to the test Heisenberg’s uncertainty principle, and the whole Copenhagen interpretation along with it. At the time, Popper was able to count on the strong support of physicists such as Jean-Pierre Vigier and Franco Selleri, who were harsh critics of the Copenhagen interpretation of quantum physics (see Freire 2004; Del Santo 2018).

Initially conceived as a thought experiment, Popper’s EPR-like proposal eventually found its way, at the end of the twentieth century, onto lab benches thanks to Yanhua Shih. The interpretation of this experiment triggered a lasting debate that survived Popper himself, as Kim and Shih’s results (Kim and Shih 1999) were disconcerting and triggered a real stir, which still deserves historical investigation. In hindsight, we may say that much of the debate was related to a poor understanding, even among physicists, about “entangled” pairs of photons. Indeed, the issue was reviewed, a decade later, by Tabish Qureshi, whose resolution of this issue states: “[Popper’s] experiment, by its very nature, cannot be decisive about Popper’s test of the Copenhagen interpretation, a point missed by both Popper and the defenders of the Copenhagen interpretation” (Qureshi 2012). Qureshi concludes that “Popper’s experiment has proved to be useful in understanding what quantum correlations are, and more importantly, what they are not.”

In a nutshell, Popper’s ideas on the foundations of quantum mechanics may be summarized as being based on the assumptions of both *realism* and *indeterminism.* Indeed, he fully accepted the intrinsically probabilistic nature of physical processes (actually also at the classical level) and, motivated by this, he suggested his propensity interpretation as an interpretation of probability which later was converted into an interpretation of quantum mechanics. Without any attachment to determinism, Popper criticized the introduction of subjectivist approaches in this scientific domain, aligning himself with the realist position in the quantum controversy, while harshly criticizing the widespread Copenhagen (or orthodox) interpretation (see Freire 2015).

In this chapter we present a chronologically organized overview of Popper’s concerns with quantum mechanics, and, as an epilogue, we summarize the debates about the experiment he had suggested, and assess the resonance of Popper’s indeterministic view on current research in (quantum) physics.

2 Popper and Quantum Mechanics

2.1 Popper's Early Concerns with Quantum Theory (1934)

Remarkably, Popper's engagement in the debate over the foundations of quantum mechanics dates back to the early days of the theory, and eventually lasted for the rest of Popper's life. As early as 1934, Popper conceived a thought experiment which was devised to advocate a statistical interpretation of the Heisenberg's uncertainty relations, as opposed to a fundamental limitation to the determinacy of conjugated variables in a single quantum system. In Popper's words, this thought experiment turned out to be "a gross mistake for which [he had] been deeply sorry and ashamed of ever since" (Popper and Bartley 1982); and yet this accident allowed him to confront the founding fathers of quantum physics—among whom figure the names of Einstein, Heisenberg and Bohr—and it possibly even had some influences on Einstein in his subsequent development of the EPR paradox (see Jammer 1974, 178). However, Popper's mistake (together with the tragic historical events that shook Europe in the 1930s and1940s) led Popper away from the quantum controversy for over a decade.

It was only in 1948 that Popper returned to think about problems of quantum foundations, mostly thanks to the encouragement of his friend, the Austrian physicist Arthur March (see Popper 1976, 106). It was around the same time that Popper's ideas on indeterminism began to take shape: In November 1948, he gave a first talk at the British Society for the History of Science on "Indeterminism in Quantum Physics and in Classical Physics"; he then presented the same topic in a course of lectures he held at Harvard University, and again in 1950 in Princeton in front of Einstein and Bohr (see Del Santo 2019). These ideas appeared in print, too, soon after (Popper 1951). Popper proposed the novel view that both classical and quantum physics can (and ought) to be interpreted indeterministically (as we will see in Sect. 3.2, these ideas had an influence on similar recent developments).

Through the radicalization of his stance regarding indeterminism in physics starting from 1953 Popper developed the conceptual tool of "propensities", namely objective intrinsic probabilities that determine the tendency for a certain physical process to happen in a genuine indeterministic way. This innovative idea brings together physical (indeterministic) processes and mathematical probabilities in a natural way. Popper, in fact, proposed "that probabilities must be 'physically real'—that they must be physical propensities, abstract relational properties of the physical situation" (Popper 1959). He publicly presented this interpretation of probabilities for the first time in April 1957, at the "Ninth Symposium of the Colston Research Society in Bristol", publishing two papers on this topic (Popper 1957, 1959).

As a matter of fact, it should be noted that throughout the 1950s, while being explicitly physically motivated, the propensity interpretation remained no more than a formal interpretation of the calculus of probability and its resonance among physicists was negligible at the time. As we shall see, Popper's role in the quantum debate was to be drastically boosted in the following decade, when his propensity interpretation became an actual comprehensive attempt to interpret the quantum theory.

2.2 The Turning Point: From Philosophy to Physics (Ca. 1967–1968)

Before moving forward to discuss Popper's further contributions to the quantum controversy, a clarification of a more sociological nature seems due. In fact, as argued in detail in (Del Santo 2019), there is good evidence to maintain that up until 1960s none of the aforementioned efforts that Popper made in the field of foundations of quantum mechanics had almost any influence in the community of physicists (besides the mistaken thought experiment of 1934). As a matter of fact, in those years Popper was a reference point for some physicists, notably Alfred Landé, David Bohm and Hermann Bondi, with some interest in philosophy. He helped them to network and even publish philosophical papers, but the resonance of his own ideas among physicists remained scarce. It was only in the mid-1960s, thanks to new acquaintanceships with physicists who were active also in the community of philosophers of science—in particular Wolfgang Yourgrau and Mario Bunge—that Popper's ideas started to become influential among physicists. This led to the real turning point of Popper's role in the quantum debate, namely the publication of two papers, "Quantum Mechanics without the Observer" (Popper 1967; see also Del Santo 2019) and "Birkhoff and von Neumann's interpretation of Quantum Mechanics" (Popper 1968; see also Del Santo 2020), which projected Popper into discussions with several physicists active in the foundations of quantum theory.

In the latter of these two papers, Popper claimed that an extremely influential proposal by Garrett Birkhoff and John von Neumann (Birkhoff and von Neumann 1936)—which initiated the subfield known as the "logic of quantum mechanics" (LQM)—was formally flawed. LQM is an axiomatic approach to quantum theory that describes physical systems in terms of "yes-no questions" (or empirical propositions) and investigates the algebraic structures of the logical connectives that relate them, which are compatible with the observed phenomenology. Now, in classical physics, the state of a system is a mathematical point in phase-space, thus any yes-no question, e.g. "is the position of a particle in the interval [0,1]?", has a fully determined truth value at each time; and so it is the conjunction and the disjunction of any two propositions. It can be shown that the empirical propositions of classical physics are compatible with Boolean algebra. On the other hand, in their pioneering work, Birkhoff and von Neumann showed that Boolean logic is incompatible with the phenomenology of quantum mechanics, due to Heisenberg's uncertainty principle.[1] In the late 1960s, LQM was experiencing a revival, specially due to the "school of Geneva" which gathered around the figure of Joseph-Maria Jauch. It was this renewed interest that led Popper to write a critical paper against the whole approach, which was rooted in the standard interpretation of the uncertainty relations (considered by

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[1] Technically speaking, what fails in quantum mechanics is the distributive law (which is one of the properties that characterizes Boolean algebra) for empirical propositions, due to the existence of incompatible observables (i.e. not commuting operators); see (Del Santo 2020) and references therein for further details.

Popper a crucial part of the Copenhagen interpretation), which Popper had already tried to dismantle in the 1930s.

It would be impossible to analyze here Popper's criticisms in detail. They are rather technical, but, as a matter of fact, they turned out to be mostly based on misconceptions, as also later acknowledged by Popper himself (who, in fact, did not reproduce any of these arguments in his book on the philosophy of quantum theory: Popper and Bartley 1982). Nevertheless, from the historiographical point of view, Popper's critique of LQM is an interesting case. In fact, the reputation of Popper as a philosopher and of Birkhoff and von Neumann as mathematicians, together with the distinction of the journal *Nature* on whose pages the paper appeared, made historians wonder why this incident did not trigger a broad debate. Indeed, only recently has one of the present authors (FDS) reconstructed the genesis of Popper's efforts against LQM in detail, and has shown that not only the short paper in *Nature* (Popper 1968) was merely one of five manuscripts (the others remained unpublished but are now partly retrieved, see Del Santo 2020), but also that this debate did happen albeit in the form of private correspondence. Indeed, Popper had a sustained epistolary exchange with many of the protagonists of the new LQM and Jauch in particular. The latter even went as far as accusing Popper of collusion, when a critical comment by Arlan Ramsay and James C. T. Pool was rejected by *Nature*. He wrote to Popper: "You have published in a widely read periodical criticisms of an important paper, which you have certainly misunderstood. [...] You realize of course that the entire scientific progress depends on the possibility of free exchange of scientific information and criticism. [...] Did you not say yourself in the "Open Society and its Enemies" the spirit of science is criticism. If you believe that, I suggest that you send the enclosed copy of the manuscript by Ramsay and Pool to Nature with your personal request that it be published." (Letter to Popper on February 24th, 1969. Reproduced from Del Santo 2020). This triggered Popper's outrage, who replied: "I do not see what can give you the right to suppose that there is a need to remind me of this; or what your remark may mean unless you wish to accuse of dishonesty." (letter from Popper to Jauch on February 28th, 1969. Reproduced from Del Santo 2020). Although Popper solicited the publication, this critical comment never appeared in print but, thanks to the interaction with the mathematician Simon Kochen, Popper eventually was persuaded that his criticisms were based on a misunderstanding of the original paper of Birkhoff and von Neumann (which admittedly had some ambiguous definitions). It ought to be stressed, however, that this period of intense debate with a number of physicists and mathematicians—besides the aforementioned Jauch, Ramsay, Pool, and Kochen, also David Finkelstein, Abner Shimony, de Broglie—clearly helped pave the way for Popper's entrance into the community of quantum foundations in the following years.

However, the publication that most of all broke the ice for Popper's interaction with quantum physicists was "Quantum Mechanics without the Observer'" (QMwO), which even today arouses some theoretical interest, besides its historical importance. In the paper Popper presents a physical interpretation of quantum mechanics, and propensities are no longer merely an interpretation of probability from which one could indirectly infer an interpretation of quantum mechanics. He presents what a little later became well known as the statistical or ensemble interpretation of quantum mechanics. Indeed, in 1970, Leslie Ballentine christened "The Statistical Interpretation of Quantum Mechanics," as the interpretation "according to which a pure state (and hence also a general state) provides a description of certain statistical properties of an ensemble of similarly prepared systems, but need not provide a complete description of an individual system," and attributed it to Einstein, Popper, and Blokhintsev (Ballentine 1970, 360). Twenty years later Dipankar Home and M. A. B. Whitaker reviewed the statistical interpretation, rechristened it as the "ensemble interpretation," and related it to the diverse interpretations of probabilities. Popper is presented, again, as an advocate of such an interpretation. Thus, it is beyond doubt that with QMwO, Popper entered the physics scene as a proponent of a physical interpretation of quantum mechanics.

Popper presented his views in the schematic form of 13 main theses. For him, quantum mechanics is a theory about statistical problems, such as black-body radiation, and not about atomic stability (1st thesis); "statistical questions demand, essentially, statistical answers, thus quantum mechanics must be, essentially, a statistical theory" (2nd thesis, p. 170); and, this way, there is no "no lack of knowledge, which allowed the intrusion of the observer," (3rd thesis). The following thesis is about what Popper called the "great quantum muddle," a view about the object of statistical distributions. According to Popper, statistical distribution functions "may be looked upon as *a property characterizing the sample space*," [as] "it is *not* a physical property characteristic of the *events* […]; still less is it a property of the *elements*." Thus, "the great quantum muddle consists in taking a distribution function, i.e. a statistical measure function characterizing some *sample space* […], and treating it as *a physical property of the elements of the population.* It *is* a muddle: the sample space has hardly anything to do with the elements." The philosophical sophistication of these remarks did not pass by commentators unnoticed (Home and Whitaker 1992, 280).

Popper continued by stating, in the 5th and 6th theses, that formulae such as Heisenberg relations are statistical scatter relations (as he had already maintained since 1934). He presented an approximate derivation of these relations departing from equations of classical physics, optics for instance. In these derivations Popper assumed quantum systems as always having well defined properties such as positions and momenta previous to the measurement. It is also noticeable that Popper did not strictly appeal to the quantum mechanics mathematical formalism. In the 8th thesis Popper suggested that while quantum mechanics is a statistical theory, it is applicable to singular systems. But these systems are not things such as electrons. Indeed, for Popper, probability statements are "statements about some measure of a property (a physical property, comparable to symmetry or asymmetry) of the whole experimental arrangement; a measure, more precisely, of a virtual frequency" (p. 32). Thus "propensities are properties of neither particles nor photons nor electrons nor pennies. They are properties of the repeatable experimental arrangement - physical and concrete, in so far as they may be statistically tested" (p. 32). Some readers would see a rapprochement to Bohr's position here; but far from this, Popper's position was grounded on an explicit defense of realism, as we are going to see. Before this, Popper's last thesis was the statement that he was not concerned with the quantum indeterminism. Reasons for this go beyond the consideration of the quantum case and encompass the whole of physics; for him, "both classical physics and quantum physics are indeterministic" (p. 40).

Popper's realism was larger than the assumption, so common among physicists, of the existence of a reality independent of the existence of an observer. He called for the distinction between theories and concepts, and assumed that theories are statements about the world. Thus, it would be wrong to take physical theories as "conceptual systems" or "conceptual frameworks." He acknowledged that "it is true that we cannot construct theories without using words or, if the term is preferred, 'concepts'." But insisted "it is most important to distinguish between statements and words, and between theories and concepts." While grounded on the logical distinction between words and statements, Popper had a precise target in the world of quantum physics. Indeed, he criticized all the physicists who, following Ernst Mach, defended the view that physical theories are mostly about concepts, calling this is an instrumentalistic view of science. Finally, he criticized Niels Bohr for adhering to Mach's position, and concluded by criticizing the idea of complementarity between the wave picture and the particle picture as a tenet of quantum theory, as pictures could not be essential parts of a physical theory.[2]

QMwO, which was urged by Bunge and published in a volume edited by him, was perhaps the Popper's first paper (since the 1930s) targeting an audience of physicists. And indeed, it soon started to bear fruit: Bohm was the first to write to Popper praising his propensities[3]: "I feel that what you have to say about propensities makes a genuine contribution to clarifying the issues that you discuss." (Letter from Bohm to Popper, on March, 3rd 1967. Reproduced from Del Santo 2019). Also Landé and Bondi, who both were friends with Popper, reacted positively to QMwO. However, what is remarkable is that the resonance of Popper's paper transgressed his usual circle of acquaintances. Among others, Bartel L. van der Waerden—a former pupil of Emmy Noether in Göttingen a close collaborator of Heisenberg in Leipzig—wrote to Popper concerning QMwO: "I fully agree with your 13 theses, and I feel it was very good you expounded them so clearly. I also agree with your propensity interpretation of probability. […] I feel my ideas are in perfect accordance with your theses" (letter from van der Waerden to Popper, on October 19th, 1968. Reproduced from Del Santo 2019). Finally, also the French Nobel laureate and founding father of quantum theory, Louis de Broglie, wrote to Popper: "I noticed with great pleasure that your ideas are very close to mine". (de Broglie to Popper, on March 4th, 1969. PA 96/7. Reproduced from Del Santo 2019).

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[2] All citations from Popper (1967, 11–14).

[3] It should be stressed that Bohm was present at the first symposium in 1957, when Popper's propensities were first presented. Moreover, he had been regularly in touch with Popper for a decade since then, but it seems that he was not aware of propensities yet. This corroborates our thesis that up until QMwO physicists, even those close to Popper, paid little attention to Popper's ideas related to quantum foundations.

Popper's QMwO also received several rebuttals: Jeffrey Bub, a former student of Bohm in London, rejected Popper's propensities (Bub 1972; see Jammer 1974, 452–453), showing that Popper's interpretation of quantum theory in terms of propensities is problematic because it is an interpretation of a still Boolean probability calculus which is not compatible with quantum probability. Such a criticism was similar to that levelled by Paul Feyerabend, who published a vitriolic rebuttal (Feyerabend 1968) of Popper's QMwO, in the course of his vaster critique of Popper's ideas in those years.[4]

In point of fact, Popper's role in the quantum debate changed drastically after the late 1960s, and his influence among physicists became appreciable. In particular—more than likely through the common friendship of Bohm—Popper got to know Jean-Pierre Vigier, a French physicist, pupil of de Broglie, who had contributed a great deal to the realistic program in quantum foundations. He was to become a valuable ally for Popper, and it is mostly thanks to his encouragement that Popper entered his last period of activity on quantum foundations, this time fully within the community of physicists.[5]

2.3 The Mature View: Popper's Experiment (The 1980s)

Popper entered the 1980s, well into his eighties, with a new turn in his intellectual life. This was related to the space he opened to the research in quantum mechanics. Thanks to the regular interaction with Vigier, he had been thinking about new experimental proposals to confirm the realistic interpretation of quantum theory, while ruling out the Copenhagen one. And, indeed, in June 1980, Popper devised a variant of the EPR experiment—currently known as Popper's experiment—to enlighten the foundations of quantum mechanics (see Del Santo 2018). This was, however, published only two years later in the long awaited three volumes of the *Postscript* to the *Logic of scientific Discovery*, which were fully dedicated to the philosophy of science. Most of the content of the volumes in this series had already been written in the late 1950s but had not been published due to Popper's health issues and other incidental reasons. The third volume, entirely dedicated to the interpretation of quantum mechanics, was meaningfully entitled *Quantum Theory and the Schism in Physics* (Popper and Bartley 1982). Moreover, Popper strengthened his engagement with physicists more than ever before: he authored papers published in physics journals, established lasting intellectual relationships with some of the protagonists of the quantum debate (notably, besides Vigier, with Franco Selleri and the initiators of the

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[4] Sect. 3.4 of (Del Santo 2019) is devoted to the debate between Popper and Feyerabend triggered by the publication of QMwO. A dedicated paper is in preparation: Del Santo, F. "Beyond method: The diatribe between Feyerabend and Popper over the interpretation of quantum mechanics", to appear in a special issue edited by M. Stuart and J. Shaw on "Feyerabend and the History and Philosophy of Physics" in *Studies in History and Philosophy of Modern Physics.*

[5] It should also be remarked that Popper has been among of the first authors to respond in print to the pivotal result of Bell's theorem, at a time when it was completely overlooked (Popper 1971).

revival of foundations of quantum mechanics in Italy) and he was also appointed member of advisory committees of international physics conferences on quantum foundations. In this way, Popper lent his intellectual and social prestige to the cause of the "quantum dissidents", namely, those physicists fully dedicated to the development of research on the quantum foundations.[6]

This stage of Popper's activities was to leave a legacy which would continue to be fruitful years after Popper's passing. In the late 1990s, the physicists Yanhua Shih and Yoon-Ho Kim performed the experiment Popper had suggested and this still arouses debate today. And yet, Popper's criticisms towards determinism in the foundations of quantum and classical mechanics would resonate with later physics research in these domains.

Thus, in the 1980s, based on these ideas, Popper was ready to have stronger interaction with physicists than he had had so far. He collaborated with Vigier and the Italian young physicist Augusto Garuccio (a pupil of Selleri) to suggest a new experiment to test the existence of the empty waves Louis de Broglie had suggested in the mid-1920s. Furthermore, Popper presented the aforementioned modified version of the EPR experiment in order to invalidate Heisenberg's relation, as interpreted according the orthodox manner, and tried to persuade physicists to perform it. Indeed, this experiment was the true novelty in *Quantum Theory and the Schism in Physics*. The background and history of these experiments have been narrated in detail by one of the authors (FDS), so just to summarize here.

In 1952, David Bohm had suggested his interpretation in terms of hidden-variables (Bohm 1952), without previous knowledge of Louis de Broglie's earlier works (see Freire 2019). In fact, Bohm had developed what we call the pilot wave model in order to overcome some criticisms Wolfgang Pauli had addressed to this work. De Broglie then came back to his earlier ideas, but instead of defending the pilot wave model he had presented at the Solvay Council in 1927, he resumed ideas he had published before that. De Broglie called these ideas, in fact a model and a research program, the double solution. De Broglie meant to represent quantum systems by two equations, the first describing a wave guiding a particle (similar to solutions of the Schrödinger's equation), and the second, a nonlinear and so far unknown equation representing the particle itself. During the 1950s, neither Bohm nor de Broglie tried to test their ideas to the usual interpretation on the lab benches. Indeed, they emphasized their empirical equivalence. In the late 1970s, under the influence of the experiments on Bell's theorem, which opposed quantum mechanics to theories based on the assumption of local realism, Vigier began to look for experiments to test de Broglie's double solution. Until then, it had also been known as the "empty wave" because in the two-slits experiment, it suggests the particle passes through one of the slits and the wave passes through both slits, thus there is an empty wave through the slit where the particle did not pass. In the early 1980s, Vigier and Garuccio were suggesting a modified Mandel-Pfleegor experiment to test the empty wave proposal and invited Popper to co-author the papers with such a proposal. Popper accepted for he was sympathetic with the empty wave proposal which was, in fact, compatible with

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[6] Popper and Bartley (1982), Del Santo (2018), Freire Junior (2015).

the statistical interpretation Popper was advocating: On the one hand, the statistical interpretation was silent about physical models governing individual systems, and, on the other hand, the empty wave was silent about the equation governing the particle. If Vigier had suggested an experiment to test the Bohm-de Broglie pilot wave, instead of the double-solution (empty wave) idea, we may wonder Popper would have difficulty joining the enterprise as the pilot wave was deterministic and Popper had maintained that both quantum and classical physics are indeterministic (see above). The suggested experiment, however, did not materialize.[7]

Regardless of the joint papers on the empty wave (but admittedly stimulated by discussion with Vigier), Popper presented in his *Quantum Theory and the Schism in Physics,* in Sect. 9 of the preface of this book, what is nowadays known as Popper's experiment (PE). It was presented as "a simple experiment which may be regarded as an extension of the Einstein-Podolsky-Rosen argument." Indeed, despite the apparent similarity with the EPR experiment, there are substantial differences between them. While EPR exhibited and refused the quantum nonlocality, PE was conceived to reveal limitations in Heisenberg's uncertainty relations, or, to be more precise, in a certain interpretation of Heisenberg's relations. Popper assumed a pair of quantum particles were created and emitted (coaxially) in opposite directions, then he suggested a positronium as the source for a pair of photons, each one passing through a slit, A and B, and which were detected on screens behind the slits. The slits may be moved. Popper's drawing illustrates the idea (Fig. 1).

From the width of the slit A we may obtain the scattering of the position of the particle on the right-hand side in the y direction, thus Δq_y and, through Heisenberg's relations, the uncertainty in the momentum Δp_y. As the particles were emitted in opposite directions, one can infer the same Δq_y for the left particle, thus also its Δp_y. The p scatter may be measured through the angle of the detectors being fired at the screens. Now let us follow Popper's argument in his own words (Popper and Bartley 1982, Preface, Sect. 9):

> Now we make the slit at A very small and the slit at B very wide. [...] we have measured q_y for both particles (the one passing through A and the one passing through B) with the precision Δq_y of the slit at A, since we can now calculate the y-coordinate of the particle that passes through B with approximately the same precision, even though its slit is wide open. We thus obtain fairly precise '*knowledge*' about the q_y position of this particle—we have 'measured' its y position indirectly. And since it is, according to the Copenhagen interpretation, *our knowledge* which is described by the theory—and especially by the Heisenberg relations—we should expect that the momentum p_y of the beam that passes through B scatters as much as that of the beam that passes through A, even though the slit at A is much narrower than the widely opened slit at B. Now the scatter can, in principle, be tested with the help of the counters. If the Copenhagen interpretation is correct, then such counters on the far side of B that are indicative of a wide scatter (and of a narrow slit) should now count coincidences: counters that did not count any particles before the slit at A was narrowed.

Popper concludes, "to sum up: if the Copenhagen interpretation is correct, then any increase in the precision of our *mere knowledge* of the position q_y of the particles

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[7] On the Solvay council, see Bacciagaluppi and Valentini (2009); on de Broglie's story of his interpretations, see de Broglie (1956). The two papers co-authored by Popper are Garuccio et al. (1981a, b).

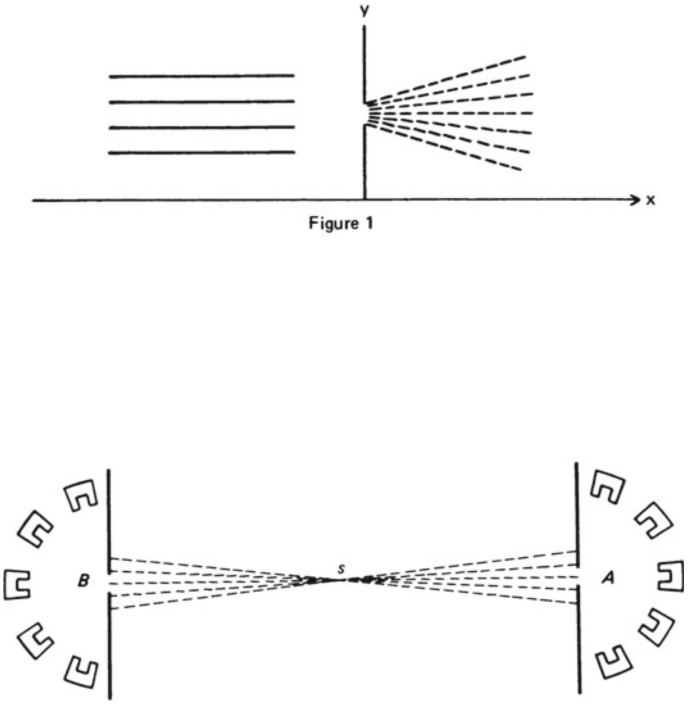

Fig. 1 Reproduction of Figs. 1 and 2 of Popper's postscript to the logic of scientific research (1982, 17 and 28, respectively), portraying Popper's EPR-like experiment. With permission of University of Klagenfurt/Karl Popper library. All rights reserved

going to the left should increase their scatter; and this prediction should be testable," and follows expressing his own expectations about the suggested experiment and its distinct implications.

Having published his suggested experiment in a book, not the place physicists would usually look for new ideas, Popper began his peregrination to convince the scientific community about the relevance and feasibility of the experiment. Towards this goal, connection with Selleri was instrumental. Introduced to the Italian physicist by Vigier, Popper was invited to attend a conference Selleri was organizing in Bari in 1983 to which Selleri had invited a few physicists just to listen Popper and discuss his experiment. The debates gathered people such as Marcello Cini, Francesco De Martini, Karl Kraus, Trevor Marshall, Helmut Rauch, Gino Tarozzi, C. Robinson, J. Six, in addition to Selleri and Vigier themselves. Most of the debate concerned the feasibility, more particularly how to obtain from a point source, a collinear pair of photons compatible with the width of the slits in suggested experiment. Noticeably, nobody noticed that the joint detection of the particles in the two screens implied describing them through an entangled state of the two particles, thus they could not be described as independent systems. After the Bari conference, Popper kept up the discussion of his suggested experiments but ultimately nothing materialized to bring the thought experiment to the world of real ones.[8]

Popper's activities from the late 1960s to the 1980s had an intellectual influence on the research on the foundations of quantum mechanics beyond the influence of his philosophical and scientific ideas. He was already an influential philosopher in the public sphere and brought this prestige to the "quantum dissidents", i.e. the small number of physicists who were challenging the dominant views on the interpretation of quantum mechanics and badly in need of support at those times. A letter from Selleri to him encapsulates the debt the quantum dissidents had to the Austrian philosopher: "This is the real strong idea [realism] that we have in common and I am always very grateful for the great battle you fought and you fight against the idealistic conceptions of the Copenhagen school. You gave us some water in which we can now try to swim."[9]

3 Epilogue: Popper's Legacy in Quantum Physics

3.1 Kim and Shih, and the Real Popper Experiment

The experiment suggested by Popper had an afterlife that would have surprised and pleased him, but he was no longer alive to follow its developments. The subject was resumed in the mid-1990s, when Garuccio explained PE to the Sino-American physicist Yanhua Shih, at the University of Maryland at Baltimore County. The latter immediately got down to work and carried out the experiment with his colleague Yoon-Ho Kim soon after. Shih had been one of the pioneers in the use of a more efficient source of pairs of entangled photons, parametric down conversion (PDC), for experiments in quantum optics. This technique consists of obtaining a pair of entangled photons thorough the nonlinear interaction of one photon of higher energy with a crystal. Indeed, interferometry experiments using PDC photon pairs were pioneered by the two following teams: Carroll Alley and Yanhua Shih at the University of Maryland and Ruba Ghosh and Leonard Mandel at the University of Rochester (Greenberger et al. 1993, 22). Kim and Shih circumvented the issue of obtaining a pair of collinear particles from a point source through the ingenuity of the use of another technique, that of ghost image with the use of a converging lens. The experiment attracted the attention of Vigier and Garuccio, who contributed to the discussion of the experiment.

Kim and Shih's results (Kim and Shih 1999) were disconcerting and triggered a stir not only because of the results themselves but also because the original paper was refused by two very prestigious journals (*Nature* and *Physical Review Letters*), before

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[8] Tarozzi and van der Merwe (1985). For the debates on the PE experiment in the early 1980s, see Del Santo (2018, 64–66).

[9] Selleri to Popper, 28 November 1989, in Freire Junior (2004, 124). On the quantum dissidents, see Freire Junior (2015).

being eventually published in *Foundations of Physics.* While this journal is a place where research on the foundations of quantum mechanics is usually found, it is not a mainstream physics journal. Interestingly, the behind the scenes of the publication of this paper deserves historical investigation however, this is beyond of the scope of our paper.[10] From the beginning, the authors warned that they were dealing with entangled photons, which means their state must be described through the formalism of quantum mechanics. However, the text did not emphasize this in the introduction of the paper but only in its development. The paper is titled "Experimental Realization of Popper's Experiment: Violation of the Uncertainty Principle?". The abstract states (Kim and Shih 1999):

> An entangled pair of photons (1 and 2) are emitted in opposite directions. A narrow slit is placed in the path of photon 1 to provide the precise knowledge of its position on the y-axis and this also determines the precise y-position of its twin, photon 2, due to quantum entanglement. Is photon 2 going to experience a greater uncertainty in momentum, that is, a greater Δp_y because of the precise knowledge of its position y ? The experimental data show $\Delta y \, \Delta p_y < h$ for photon 2. Can this recent realization of the thought experiment of Karl Popper signal a violation of the uncertainty principle?

The paper follows stating, "it is astonishing to see that the experimental results agree with Popper's prediction." Still, "through quantum entanglement one may learn the precise knowledge of a photon's position and would therefore expect a greater uncertainty in its momentum under the usual Copenhagen interpretation of the uncertainty relations. However, the measurement shows that the momentum does not experience a corresponding increase of uncertainty. Is this a violation of the uncertainty principle?" Only at this point the subject is indeed explained (Kim and Shih 1999, 1850), "as a matter of fact, one should not be surprised with the experimental result and should not consider this question as a new challenge. Similar results have been demonstrated in EPR type of experiments and the same question has been asked in EPR's 1935 paper." One year later, Shih and Kim (2000) were more precise in their wording, saying right in the abstract "the experimental data show that there appears to be a violation of the uncertainty principle. This is, however as we shall argue in this paper, only an illusion provided that we take the teachings of quantum mechanics seriously."

In hindsight, we may say that much of the debate was related to a poor understanding, even among physicists, about the hierarchy among concepts such as "quantum entanglement," strictly quantum concepts on the one hand, and the classical concept of separability which has a limited validity in quantum mechanics, on the other. Entanglement, a word first coined by Erwin Schrödinger, may only be fully understood in the context of the mathematical formalism of quantum mechanics. The issue of the interpretation of PE was reviewed, a decade later, by the Indian physicist Tabish Qureshi. In order to obtain a better comprehension of the issues at stake he translated Popper's experiment, which initially dealt with continuous variables, momentum and position, to a system with discrete variables, which are easier to deal with. It is worth remarking that a similar procedure was done by David Bohm

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[10] A preliminary discussion on this issue can be found in (Del Santo 2018).

in his 1951 textbook *Quantum Theory* where he introduced the EPR for spin variables instead of momentum and position. Leaving aside the technical details, his main conclusions were that (Qureshi 2012, 28–30) "Kim and Shih correctly implemented Popper's experiment through the innovative use of the converging lens, and the results are in good agreement with the prediction of quantum mechanics and that of the Copenhagen interpretation." The way he uses the term "Copenhagen interpretation," however, should be taken with a grain of salt because for Qureshi it does not include the subjectivist feature Popper would attribute to it. In fact, for Qureshi, "from this point of view, we conclude that the Copenhagen interpretation has been vindicated. It could not have been otherwise, because our theoretical analysis shows that the results are a consequence of the formalism of quantum mechanics, and not of any particular interpretation." Thus what was at stake was just the mathematical formalism of quantum theory. But then should we conclude from this analysis that Popper committed a gross mistake? Far from it. Still following Qureshi, "However, this experiment, by its very nature, cannot be decisive about Popper's test of the Copenhagen interpretation, a point missed by both Popper and the defenders of the Copenhagen interpretation." Indeed, Popper cannot be considered the only responsible for introducing a "flawed assumption." For Qureshi, "all the defenders of Copenhagen interpretation seemed to have the same view, that is why nobody pointed otherwise, and that is the reason why there was so much surprise at the results of Kim and Shih's experiment." Qureshi concluded by noticing that "the problem was that Popper and most of his critics arrived at a wrong conclusion as to what result the experiment would yield. This was simply because no one cared to do a rigorous analysis, but used some commonly understood notions about measurement, which led them to a wrong conclusion. With a lot of theoretical and experimental work in quantum systems behind us, now we are wiser and realize that quantum mechanics is full of such pitfalls." Finally, and endorsing Qureshi's conclusions, "Popper's experiment has proved to be useful in understanding what quantum correlations are, and more importantly, what they are not."

3.2 Popper's Ideas in Contemporary Physics: The Revival of Indeterminism

We would like to conclude this chapter by assessing, as far as possible, the main intellectual marks that Popper's ideas have left on today's fundamental physics.[11] In fact, we cannot but agree with Selleri's words, when stating that "Popper's greatness does

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[11] Relevant discussions about Popper's contribution to the foundations of physics (besides the many historiographical reconstructions mentioned above) can be found in (Jammer 1991) and (Redhead 1995), respectively written at the end of Popper's career and immediately after his death. More recently, the online Journal *Quanta* devoted its first issue to Popper's philosophy of quantum physics (http://quanta.ws/ojs/index.php/quanta/issue/view/1/showToc), whereas a part (4–B) of (Javie et al. 2006) reassessed some of Popper's work on physics in modern perspective.

not and cannot lie in a series of proposals about the nature and problems of contemporary physics that are ‘all correct’, but rather in an overall framework of ideas of exceptional interest that have filtered through science [...]” (Selleri 1990, 351). We will thus not be concerned here with the groundbreaking impact of Popper’s contribution to methodology (i.e. falsificationism) on today’s physics. This is despite the fact that he did deeply change–perhaps more than anyone else–the understanding that most physicists had about their own work and influenced countless research programs (see Del Santo and Cardelli 2019).[12] We will focus here on some outstanding instances of the repercussions that Popper’s ideas on the foundations of physics had within this field of research.

Among Popper’s conceptual contributions, the one that arguably has had the broadest impact on today’s science seems to be the indeterministic nature of physics (even at the classical level). This standpoint is complemented and formalized by the propensity interpretation of probabilities, which allows (objective) causal relations to be maintained even if determinism is refuted. Indeed, “propensity is a form of causality that is weaker than determinism” (Ballentine 2016). Mauricio Suárez, who made important contributions to the propensity program, noted that “Karl Popper’s propensity interpretation of quantum mechanics is surely his most important contribution to the philosophy of physics” (Suárez 2009). Popper’s propensities have become one of the few existing established interpretations of probability in every standard manual on the foundations of probability theory; moreover, it is the only one that allows us to make sense of single-case probabilities (together with the subjective interpretation). However, the legitimacy of propensities as a proper interpretation of probability has been often challenged, notably by P. Humphreys (1985), who noted that if we are to ascribe a causal meaning to probabilities, then the Bayes’ rule for conditional probabilities lacks a meaningful interpretation. To see this, let us consider two events, say, event A “drinking a glass of lemonade”, and event B “outside it is hot”, and let us indicate with $P(A|B)$ the conditional probability of the event A, given event B. Now, if probabilities are interpreted objectively as causal dispositions, it is completely reasonable to attribute a probability to the conditional event “drinking a glass of lemonade, given that it is hot outside”. Yet, it would be foolish to state that being hot outside is causally influenced by someone drinking a lemonade, i.e. express the reversed conditional probability $P(B|A)$. In fact, Bayes’ rule, which follows from the axioms of probability, states that conditional probabilities can be reversed as follows

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

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[12] We should notice that Popper’s falsificationism does not enjoy large support among philosophers of science today, who have harshly criticized it as a too narrow and naive view. Among Popper’s critics, we ought to mention the greatly influential Thomas Kuhn and Paul Feyerabend, whereas a failure of Popper’s falsificationism in historical perspective has been recently provided by Brush and Segal (2015). Despite this, as noted by Kragh (2013), it can be contented that “Karl Popper’s philosophy of science [...] is easily the view of science with the biggest impact on practising scientists”.

where *P(A)* and *P(B)* are the marginal probabilities of observing event *A* and *B*, respectively. More generally, if probabilities are propensities, this means that they express the objective tendency of an effect to happen given a certain cause but, according to Bayes' rule, also the cause would in turn be causally influenced by the effect and this is paradoxical (*Humphrey's paradox*). Thus, Humphreys concluded that "propensities cannot be probabilities" (Humphreys 1985).

Several philosophers have vindicated Popper's propensities as fully fledged probabilities, most prominently Miller (1994). But the kind of solutions of Humphrey's paradox that they have proposed take propensities only to refer to present events, and this requires that propensities depend upon *all* past causal influences, i.e. the whole past light cone. Interestingly, some physicists (more or less aware of this) accepted Humphreys' criticism, thereby developing a theory of propensities which do not satisfy the axioms of probability (e.g. Gisin 1991; Ballentine 2016). This does not make propensities a full-fledged interpretation of probabilities, but allows them to be a useful tool to describe indeterministic physical theories.

In recent years, these ideas have, in fact, gained new impetus among physicists. Ballentine has further developed the original idea of Popper's "that the intrinsic quantum probabilities (calculated from a state vector or density matrix) are most naturally interpreted as quantum propensities." (Ballentine 2016; see also Maxwell 2011). Another novel line of research which arguably has a clear resonance with the Popperian program has been put forward by Nicolas Gisin in a series of papers (Gisin 2019; Del Santo and Gisin 2019; Gisin 2020). In these, he has challenged the foundations of classical physics, showing that the seemingly innocuous standard assumption that physical quantities take values in the real numbers leads to the unphysical possibility of storing infinite information in a finite volume. Gisin thus proposed removing any physical meaning of real numbers, and he successfully showed that this implies that even classical mechanics ought to be interpreted indeterministically, in a similar fashion as advocated by Popper himself (Popper 1950). Subsequently, a new model was proposed in (Del Santo and Gisin 2019) which makes explicit use of propensities, which are taken to be tendencies of each digit of a physical quantity to take one of the possible but not yet determinate values. In this model, propensities are posited to be rational numbers and do not necessarily fulfil the formal requirements of probabilities. In this way, classical physics is modelled as an indeterministic (though empirically equivalent) theory, in which the values of physical quantities are not predetermined, but get actualized as time elapses, through a true random, objective process, i.e. a propensity.

In conclusion, Popper's contributions to physics are neither free of misconceptions nor of formal mistakes. Yet Popper's ability to always think out of the box, his stunning conceptual clarity and simplicity of explanation, together with his ability to engage in a multiplicity of subjects (and be able to interact with their respective practitioners) provided the ground for what we believe will be a long-lasting influence on the foundations of physics. Max Jammer (1991) commented that "Popper's wit, ingenuity, and independence of thought, [...] can undoubtedly have a stimulating effect on contemporary theoretizing in physics". Moreover, we cannot avoid looking in wonder at a scholar whose consistent vision spanned all disciplines, from politics and epistemology to physics and biology, a vision of hope in the intellectual freedom of humankind. At the same time, he was able to envision that nature itself does not rule out such freedom even for its most fundamental components, such as quantum particles: “The future is open. It is not predetermined and thus cannot be predicted –except by accident. The possibilities that lie in the future are infinite” (Popper 1994).

References

Bacciagaluppi, G., Valentini, A.: Quantum theory at the crossroads: reconsidering the 1927 solvay conference. Cambridge University Press, Cambridge (2009)

Ballentine, L.E.: Statistical interpretation of quantum mechanics. Rev. Mod. Phys. **42**(4), 358–381 (1970)

Ballentine, L.E.: Propensity, probability, and quantum theory. Found. Phys. **46**, 973–1005 (2016)

Birkoff, G., von Neumann, J.: The logic of quantum mechanics. Ann. Math. **37**(4), 823–843 (1936)

Bohm, D.: Quantum theory. Prentice-Hall, New York (1951)

Bohm, D.: A suggested interpretation of the quantum theory in terms of hidden variables—I & II. Phys. Rev. **85**(2), 166–179 and 180–193 (1952)

Broglie, L.: Nouvelles perspectives en microphysique. Albin Michel, Paris (1956)

Brush, S., Segal, A.: Making 20th century science: how theories became knowledge. Oxford University Press, New York (2015)

Bub, J.: Popper’s propensity interpretation of probability and quantum mechanics. University of Minnesota Press, Minneapolis. Retrieved from the University of Minnesota Digital Conservancy. http://hdl.handle.net/11299/184671 (1972)

Del Santo, F.: Genesis of Karl Popper’s EPR-like experiment and its resonance amongst the physics community in the 1980s. Stud. Hist. Philos. Mod. Phys. **62**, 56–70 (2018)

Del Santo, F.: Karl Popper’s forgotten role in the quantum debate at the edge between philosophy and physics in 1950s and 1960s. Stud. Hist. Philos. Mod. Phys. **67**, 78–88 (2019)

Del Santo, F.: An unpublished debate brought to light: Karl Popper’s enterprise against the logic of quantum mechanics. Stud. Hist. Philos. Mod. Phys. forthcoming (2020)

Del Santo, F., Cardelli, C.: Demolishing prejudices to get to the foundations: a criterion of demarcation for fundamentality. Foundations of Science (2019)

Del Santo, F., Gisin, N.: Physics without determinism: alternative interpretations of classical physics. Phys. Rev. A **100**(6) (2019)

Feyerabend, P.K.: On a recent critique of complementarity: part I. Philos. Sci. **35**, 309–333 (1968)

Freire, O. Jr. Popper, Probabilidade e Teoria Quântica. Episteme (Porto Alegre) **18**, 103–127. (2004)

Freire Jr., O.: The quantum dissidents: rebuilding the foundations of quantum mechanics (1950–1990). Springer, Berlin (2015)

Freire Jr., O.: David Bohm: a life dedicated to understanding the quantum world. Springer Nature, Switzerland (2019)

Garuccio, A., Popper, K.R., Vigier, J.-P.: An experiment to interpret E.P.R. action at a distance: the possible detection of real de Broglie waves. Epistemological Letters, **30**, 21 (1981a)

Garuccio, A., Popper, K.R., Vigier, J.-P. Possible direct physical detection of de Broglie waves. Physics Letters A, **86**(8), 397–400 (1981b)

Gisin, N.: Propensities in a non-deterministic physics. Synthese **89**, 287–297 (1991)

Gisin, N.: Indeterminism in physics, classical chaos and Bohmian mechanics. Are real numbers really real?. Erkenntnis (2019)

Gisin, N.: Real numbers are the hidden variables of classical mechanics. Quantum Stud.: Math. Found. **7**, 197–201 (2020)

Greenberger, D.M., et al.: Multiparticle interferometry and the superposition principle. Phys. Today **46**(8), 22–29 (1993)

Home, D., Whitaker, M.A.B.: Ensemble interpretations of quantum-mechanics—a modern perspective. Phys. Rep. Rev. Sect. Phys. Lett. **210**(4), 223–317 (1992)

Howard, D.: Popper and Bohr on realism in quantum mechanics. Quanta **1**(1), 33–57 (2012)

Humphreys, P.: Why propensities cannot be probabilities. Philos. Rev. **94**, 557–570 (1985)

Jammer, M.: The philosophy of quantum mechanics. Wiley, New York (1974)

Jammer, M.: Sir Karl Popper and his philosophy of physics. Found. Phys. **21**, 1357–1368 (1991)

Jarvie, I.C., Milford, K., Miller, D.: Karl Popper: a centenary assessment vol. 3: science. Ashgate Publishing Limited, Burlington (2006)

Kim, Y.-H., Shih, Y.: Experimental realization of Popper's experiment: violation of the uncertainty principle? Found. Phys. **29**(12), 1849–1861 (1999)

Kragh, H.: The most philosophically of all the sciences: Karl Popper and physical cosmology. Perspect. Sci. **21**, 3 (2013)

Maxwell, N.: Is the quantum world composed of propensitons? In: Suárez, M. (ed.) Probabilities Causes and Propensities in Physics. Springer, Dordrecht (2011)

Miller, D.: Critical rationalism: a restatement and defense. Open Court Publishing Company, Chicago, and La Salle (1994)

Popper, Karl R.: Logik der Forschung. Zur Erkenntnistheorie der modernen Naturwissenschaft. Julius Springer, Vienna (1934)

Popper, K.R.: Indeterminism in quantum physics and in classical physics. Part I. Br. J. Philos. Sci. **1**(2), 117–133 (1950)

Popper, K.R.: Indeterminism in quantum-mechanics and in classical physics. Br. J. Philos. Sci. **1**(2), 117–133 (1951).

Popper, K.R.: The propensity interpretation of the calculus of probability, and the quantum theory. In: Körner, S., Pryce, N.H.L. (eds.) Observation and Interpretation, Proceedings of the Ninth Symposium of the Colston Research Society (1957)

Popper, K.R.: The propensity interpretation of probability. Br. J. Philos. Sci. **10**(37), 25–42 (1959)

Popper, K.R.: Quantum mechanics without the observer. In: Bunge, Mario (ed.) Quantum Theory and Reality. Springer, Berlin (1967)

Popper, K.R.: Birkhoff and von Neumann's interpretation of quantum mechanics. Nature **219**, 682–685 (1968)

Popper, K.R.: Particle annihilation and the argument of Einstein, Podolsky and Rosen. In: Yourgrau, W., van der Merwe, A. (eds.) Perspectives in Quantum Theory. MIT Press, Cambridge (1971)

Popper, K.R.: Unended quest: an intellectual autobiography. Routledge, London (1976)

Popper, K.R.: The myth of the framework: in defence of science and rationality. Routledge, London and New York (1994)

Popper, K.R., Bartley III, W. (eds.): Vol. III of the Postscript to the Logic of Scientific Discovery: Quantum Theory and the Schism in Physics. Rowman and Littlefield, Hutchinson, Totowa, London (1982)

Qureshi, T.: Popper's experiment: a modern perspective. Quanta **1**(1), 19–32 (2012)

Redhead, M.: Popper and the quantum theory. R. Inst. Philos. Suppl. **39**, 163–176 (1995)

Selleri, F.: Quantum paradoxes and physical reality. Kluwer, Dordrecht (1990)

Shields, W.M.: A historical survey of Sir Karl Popper's contribution to quantum mechanics. Quanta **1**(1), 1–12. (2012)

Shih, Y., Kim, Y.-H.: Experimental realization of Popper's experiment: violation of the uncertainty principle? Fortschr. Phys. **48**(5–7), 463–471 (2000)

Suárez, M.: Propensities in quantum mechanics. In: Greenberger, D., Hentschel, K., Weinert, F. (eds.) Compendium of Quantum Physics. Springer, Berlin, Heidelberg (2009)

Tarozzi, G., van der Merwe, A. (eds.): Open questions in quantum physics. Reidel Publishing Co., Dordrecht (1985)

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