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Review

Ontology and the foundations of quantum theory

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Abstract A brief review of the historical main line of investigation of the ontology of quantum theory is given with an emphasis on elementary particles. Einstein et al. considered possible elements of reality and questioned the completeness of the quantum state, prompting later studies of local causality in relation to their physical properties. Later reconsiderations of quantum mechanical law have involved differing attitudes toward the objective existence not only of the properties of distantly located particles, but even of entire universes of systems including them. Experimental foundational investigations have mainly involved quantum mechanics at low energies but some have begun to explore higher energies, where quantum field theory is required, and its ontology has been seen to involve quantum fields as well as elementary particles.

1 Introduction

Any natural science involves an ontology including the posits of its best theories, that is, what things exist and how according to them. Because physics is the most fundamental natural science, its ontology is due particular attention. But, being the most precise and successful science, the questioning of the ontology of physics was not often considered necessary in the many decades preceding the advent of quantum theory; instead, the focus of physical research was largely on problem solving and the provision of clear descriptions and explanations involving matter and light within its also well accepted mathematical framework (cf. [1] Sect. III). When considered, ontological questions of physics were the perennial questions of the (non)absolute nature of space, the (in)divisibility of matter, and the (im)possibility of a vacuum (cf. [2, 3]), binary choices between long-considered alternatives. With the radical shift to quantum theory, however, ontological questions were actively reconsidered and eventually came to involve several alternatives, associated with different interpretations of it. In early quantum mechanics (QM), representations (considered concretely as such by Erwin Schrödinger [4, 5], but later abstractly by John von Neumann [6]) were already in contention, cf. [7]. The quantum state and probabilities have been the focus of interpretational controversies. For example, with the study of quantum state entanglement and quantum particle statistics [8], the relationship between system wholes and parts [9] and system haecceity ("this-ness" [10]) has been called into question. In quantum field theory, the nature of elementary particles has also remained in need of clarification, as noted, e.g., by Werner Heisenberg [11]. Some, interpreting quantum probability, have even denied that quantum theory concerns physical objects [12]. Thus, ontological issues remain significant for the understanding of quantum physics.

A number of physicists have claimed that metaphysics as considered by philosophy is obfuscatory when brought directly into physical discussions, and some philosophers have said that physicists generally have imprecise views regarding ontology. Some physicists who have engaged in the interpretation of quantum theory after its founders—for whom interpretation was unavoidable since the formalism of fundamental physics had changed—have said that quantum mechanics "needs no interpretation" or is 'self-interpreting' or involves "interpretation without interpretation," and even that "quantum theory does not describe physical reality" [12]. But, to be used, every theory requires some interpretation which itself has metaphysical relevance, even if that is only the simple statement that it has no ontological commitment and regards only knowledge. It has been said that physicists with traditional views generally consider that "If an experiment reveals 'somewhat directly' a physical entity corresponding to the theoretical element in question, then that entity is physically real and is more or less the way the theory

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says it is" [13], p. 125. Such a straightforward approach to physical ontology might, indeed, appear problematic given that theory changes rather radically from time to time, as in the recent transition from classical to quantum physics: Scientific realism is susceptible to the pessimistic meta-induction (cf. [14], pp. 143–149), which suggests that physical theory cannot provide a correct literal description of the world because physical theories change radically, as they did both in the transition to modern physics from the intuitive, classical physics and during the extended scientific revolution of the second millennium which first accelerated its mathematization.

Here, the engagement of the foundations of quantum theory with ontology is reviewed via its theoretical explorations and subsequent experimental results, and the ontology of the most well-developed sort of quantum theory, relativistic quantum field theory including interactions, which describes specific systems actually used in quantum experiments, is considered in the broadest terms.

2 Theoretical approaches to ontological questions

The ontology of a physical theory is related to its terminology, principles, and formalism by its interpretation.[1] A rough distinction between types of interpretation of quantum theory is that between those which are explicitly ontological (under consideration here), in which the state is to specify its physical objects, properties, and their relations and those which are primarily epistemic, in which quantum probabilities are to provide knowledge without necessarily having significant novel ontological commitment. The most influential of the latter is the Copenhagen interpretation (explicitly called such in [17]), initiated by Niels Bohr but having several manifestations, that allows calculation (say, using Paul Dirac's formalism [18]), primarily for predictive purposes, of observable eigenvalues as manifested in classical instruments. Karl Popper called its advocates "end-of-the-road people" because it did not require of physicists that they further investigate the ontology of quantum objects ([19], p. 13). At the other end of the range of ontological commitment is the many-worlds interpretation of quantum mechanics, which explicitly considers the quantum mechanical equation of motion as everywhere applicable and unitary, so state-deterministic and with an ontology of distinct instantiations of all observable eigenvalues upon density matrix diagonalization, each value occurring in a different, actual universe [20–22].

The significance of quantum theory for ontology became starkly evident even before the many-worlds interpretation was offered, when Einstein, Podolsky, and Rosen (EPR) [23] drew dramatic conclusions from the assumption that quantum mechanics is a fundamental theory and Schrödinger used his Cat thought experiment to illustrate apparently absurd implications [24]. Both Einstein and Schrödinger saw quantum mechanics, if taken as complete—as opposed to providing only statistics of ensembles of incompletely described systems or of a limited range of systems—as at odds with realism and experience. In a letter to Schrödinger, Einstein wrote, "Most [physicists] simply do not see what sort of risky game they are playing with reality—reality is something independent of what is experimentally established. They somehow think that quantum theory provides a description of reality, and even a complete description; this interpretation is, however, refuted most elegantly by your [experiment]...system of radioactive atom + Geiger counter + amplifier + charge of gun powder + cat in a box, in which the ψ-function of the system contains the cat both alive and blown to bits...Nobody really doubts that the presence or absence of the cat is something independent of the act of observation" ([25], p. 39).[2] This example strongly pointed out the importance of difference between the epistemic, knowledge-based and the ontic understanding of the quantum state, that is, between taking the state as a direct representation of reality versus taking it to provide information as to the physical properties of the system to which it can be associated. Realist physicists also began cautiously to reconsider the requirements on what constitute physical laws, as quantum physics has moved increasingly from the realm of such thought experiments toward practical experiments and model the measurement process in accordance with such perspective.[3]

The EPR argument involves a state of the kind Schrödinger was first to call entangled [24] and questioned whether, according to quantum mechanics, physical properties as "elements of reality" are always independent outside the range of mutual local influences. In time, the study of such states both doomed the idea that anything but the simplest of quantum systems might behave like classical waves (an interpretation Schrödinger had considered [32]) and led to a better understanding of quantum state and observable spaces for multipartite quantum systems (cf. [33, 34]

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[1] Discussions of the range of interpretations are found in, e.g., [15, 16].

[2] A good contemporary characterization of a realist interpretation of quantum theory sensitive to the semantic aspect of interpretation is: "[A]ccepting that [quantum theory] is true, that the objects [it] refers to (electrons, protons, etc.) exist, that the properties it refers to are 'real,' and in particular that the physical quantities it refers to are 'real'; in short it also means that we can...take all its referential terms as genuinely referring and not just as convenient fictions or metaphors for the real" ([26], p. 126)—reference meant here in the linguistic sense. See [27] for a discussion of philosophical challenges to realism.

[3] Two, quite difference approaches to this serve as illustrative examples of the diversity of approaches currently under pursuit: see the articles [28–31] and references therein.

Ch. 6). Einstein pursued a realist physics, holding that the "'real' in physics is to be taken as a type of program, to which we are, however, not forced to cling *a priori*. No one is likely to be inclined to attempt to give up this program within the realm of the 'macroscopic'...But the 'macroscopic' and the 'microscopic' are so inter-related that it appears impracticable to give up on this program in the 'microscopic' alone" [35], p. 674 (re macroscopicity, see [36]). The EPR argument is that quantum mechanics is incomplete because it lacks the capacity to deterministically and locally specify the values of all physical properties everywhere, something which they viewed as essential to a realist physics, and was a highly visible explicit consideration of an ontology: "Any serious consideration of a physical theory must also take into account the distinction between objective reality, which is independent of any theory, and the physical concepts with which the theory operates. These concepts are intended to correspond with the objective reality, and by means of these concepts we picture this reality to ourselves" [23].

The argument suggests quantum mechanics could not support a realist ontology without further theoretical components, for example, what have come to be known as "hidden-variables" [37, 38]. EPR discussed the quantum predictions for a two-particle system in the entangled state

$$\Psi(x_1, x_2) = \int_{-\infty}^{\infty} \exp\left[\frac{i}{\hbar}(x_1 - x_2 + x_0)p\right] \mathrm{d}p \qquad (1)$$

where x_1 and x_2 are positions, x_0 is a fixed distance, and p is momentum [23]. The correlations of measurement outcomes for local observables (represented by Hermitian operators on Hilbert space) for this state when the particles are well separated are not readily testable for this state but are so for that introduced later by David Bohm for discrete bivalent observables, namely, the spin-singlet state

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) \qquad (2)$$

the arrows here indicating the z-spin states for two spin-1/2 subsystems S_1, S_2 of their joint system S, with which the EPR argument can be more clearly made. This state also has the striking property of remaining of the same anti-correlation-bearing form when re-expressed in any orthonormal eigenstate basis obtainable from the z-spin basis by rotating the eigenstates of either subsystem Hilbert space by an arbitrary angle ξ [39]; it is maximally entangled.

EPR introduced three conditions in their argument. (1) The Reality criterion, defining the portion of "physical reality" under consideration: "If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity."[4] (2) Locality: "Since at the time of measurement the two systems no longer interact, no real change can take place in the second system in consequence of anything that may be done to the first system." (3) Completeness (which, they ultimately argued, quantum mechanics fails to satisfy): "Every element of the physical reality must have a counterpart in the physical theory." Using $|\Psi^-\rangle$, the argument involves two propositions [40]: (I) if an agent can perform an operation that permits it to predict with certainty the outcome of a measurement without disturbing the measured spin, then the measurement has a definite outcome, whether this operation is actually performed or not; (II) for a pair of spins in the state $|\Psi^-\rangle$, there is an operation that an agent can perform allowing the outcome of a measurement of one subsystem to be determined without disturbing the other spin. If the quantity with the projector $P(|\uparrow\rangle) \equiv |\uparrow\rangle\langle\uparrow|$ is measured for one system, the value of the quantity with the projector $P(|\downarrow\rangle)$ onto the orthogonal state is also fully specified. By (II), one can similarly obtain the values of the same two observables of the second system without having an influence on it because the two spins involved are anti-correlated in state $|\Psi^-\rangle$. By (I), the values of the second spin are, therefore, definite. But, one could have measured the quantities corresponding to a different basis, say, $P(|\nearrow\rangle)$ and $P(|\searrow\rangle)$. But these other values must then be definite as well. Therefore, the value of the states of both systems for all values of ξ must be definite given the assumptions (1)–(3). The description of the system of particles by the quantum state $|\Psi^-\rangle$ must, therefore, be incomplete in a specific way. Yet, it is supposed not to be. So at least one of the assumed conditions (1)–(3) must fail to be satisfied.

Einstein later commented that "on one supposition we should, in my opinion, absolutely hold fast: the real factual situation of the system S_2 is independent of what is done with the system S_1, which is spatially separated from the former." ([41], p. 85). Popper reported that Einstein said, " 'it seems to me that those physicists who regard the ways of description of quantum mechanics as in principle final ('definitiv') will react to these considerations as follows: they will drop the requirement...of the independent existence of physical real things in distant parts of space; and they could rightly claim that quantum mechanics nowhere makes implicit the use of any such requirement' " ([19], p. 21). It was argued out by Bohr is his response to EPR that quantum mechanical elements of reality are dependent on the full measurement situation [42]. Ultimately, for Einstein, the problem lay "less in the renunciation of causality than in the renunciation of the representation of a reality thought of as independent of observation" (cf. [43], p. 374). And EPR pointed to Completeness as the source of the contradiction rather than Locality and/or the Reality criterion.

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[4] This condition is closely related to causality if indeterminism is the condition that "the state of a system at time t cannot in general be predicted with certainty given the history of its states priority to t" [13], p. 19.

If the quantum state provides an incomplete individual system description, then it can at best provide descriptions of ensembles of systems. A full description of individual system properties seemed to require additional, "hidden" variables to describe the individuals. Heisenberg introduced the distinction between noncontextual and contextual hidden variables in the mid-1930 s. In noncontextual models, physical states are required to fully describe a system at a given instant via a putative complete state λ—the parametric specification of the classical mechanical phase space point of a system serving as the archetype—and the outcomes of measurement of all properties, obtained as functions $A(\lambda)$, $B(\lambda)$, $C(\lambda)$, ... are independent of each other regardless of when they are performed, and so are also jointly obtainable.[5] In the "contextualistic" case, this is not so: Outcomes may depend on the quantum state, any hidden variables, and/or any aspect of the measurement apparatus or environment in that case.[6] That the quantum state requires supplementation by local hidden variables has been broadly rejected because, in particular, later experimental results (discussed in the next section) have definitively accorded with quantum predictions.

Although Bohr and Heisenberg recognized that the quantum state does not provide simultaneous precise specifications of observed quantities (cf. [49]), they, like most after them, viewed it as complete, accepting that the quantum realm is fundamentally different from the classical realm [42]. The crucial difference, for the scientific realist, between the quantum and classical ontology brought out by these discussions is that properties of quantum systems have an objective indefiniteness. Various ways of explicating this indefiniteness have been given, for example, that of quantum potentiality [50, 51] and unsharp reality [52], as alternatives to the proposed additional variables which might somehow provide precise simultaneous values for all properties. Heisenberg continued to argue, even after the appearance of quantum electrodynamics and other quantum field theories, that "we have a consistent mathematical scheme [that] tells us everything that can be observed. Nothing is in nature which cannot be described by this scheme" (reported in [53]). (For an overview as to how such a view of quantum mechanics can be considered by the realist, see [54].)

A general analysis of the difference between quantum mechanics and a local hidden-variable completion in space-time was given by John S. Bell, who delimited a border between local, classically explicable correlations between distant measurements by finding an inequality always obeyed by any local theory describing all correlations in dichotomic observables of two distant subsystems forming a bipartite, compound system. In 'plain English,' Bell said his result "comes from an analysis of the consequences of the idea that there should be no action at a distance, under certain conditions that Einstein, Podolsky, and Rosen focussed attention on in 1935..." ([55], p. 45). Later results were directly testable by experiment. Alain Aspect, John Clauser, and Anton Zeilinger received the 2022 Nobel Prize in Physics, in part, for verifying the predictions for entangled states of bipartite systems, important parts of it with Michael Horne, cf. [56]; Bell-type inequalities and violations have been steadily generalized by others, as well (cf., e.g., [57]). Bell, who correctly expected his sort of inequality to be violated by rigorous experimental testing, remained committed to ontological realism and critical of many-worlds theory ([55], p. 50).[7]

Einstein sought to complete quantum mechanics in a way that would relatively little change the size of the quantum ontology compared to the change wrought by the "many-worlds," collapse-free approach to quantum mechanics that followed, which rather than adding hidden variables to the state, assumes a standard evolution but with the state describing a full set of equally real universes. Its originator, Hugh Everett, introduced the "universal wave function" for a super-universe, also naturally including the bodies of differing copies of observing agents, not simply describing their states of knowledge [20–22].[8] Bryce S. DeWitt and R. Neill Graham pursued this approach and interpretation, which "denies the existence of a separate classical realm and

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[5] The term 'context,' however, was to arise in the later search for supplements to the quantum mechanical description of measurements performed on compound, spatially distributed systems. Abner Shimony introduced the terminological distinction between the so-called "contextual(istic)" and "noncontextual(istic)" hidden-variable models (cf. [44], Ref. 8) in 1971: "The name "contextualistic" was introduced by A. Shimony: Experimental test of local hidden variable theories, in [45], and a shortening to "contextual" was performed by [46]" [44]. Shimony identified these sorts of models as being first explicitly considered by Bell in1966 [47], but the distinction appears to have occurred first to Heisenberg in 1935.

[6] A proof of Belinfante and others effectively demonstrated the viability of contextual hidden-variables models and quantum mechanics in a 1973 publication [48], cf. [44] Ref. 12. See [37] for a discussion of contextuality as then understood.

[7] When asked, would you "prefer to retain the notion of objective reality and throw away one of the tenets of relativity: that signals cannot travel faster than the speed of light?", Bell responded in accordance with Einstein's views: "Yes. One wants to be able to take a realistic view of the world, to talk about the world as being there even when it is not observed. I certainly believe in a world that was here before me, and will be here after me, and I believe that you are part of it! And I believe that most physicists take this point of view when they are being pushed into a corner by philosophers", ibid.

[8] Some variants are said not to involve universe-splitting, such as Bub's "new orthodoxy," which is to include aspects of the Copenhagen-type interpretation [58]. But Copenhagen-type interpretations have the observer distinct from the observed object by a scale or complexity boundary ('cut'), the location of which is not determined by physics alone and taking the observer and measurement apparatus to be described classically, not quantum mechanically [54].

asserts that it makes sense to talk about a state vector for the whole universe. This state vector never collapses, and hence reality as a whole is rigorously deterministic...the state vector decomposes naturally into orthogonal vectors, reflecting the continual splitting of the universe into a multitude of mutually unobservable but equally real worlds, in each of which every good measurement has yielded a definite result and in most of which the familiar statistical quantum laws hold" ([59], p. v). There, in a valid measurement, a chain of objects, for example X, Y,..., interacts between the system of interest S and the experimenter's apparatus A up to and including the brain of its experimenter (like the Cat), and these become correlated in key properties. Upon completion of the interactions involved, the relevant part of universe has the time-evolved multipartite state

$$|\Psi\rangle = \sum_i c_i |s_i\rangle |a_i\rangle |x_i\rangle |y_i\rangle \ldots \qquad (3)$$

where $\{s_i\}$, $\{a_i\}$, $\{x_i\}$, $\{y_i\}$ etc. are the Hilbert space eigenbases for S, A, X, Y, ..., an ambiguous indication for the value of the measured quantity if interpreted as describing one world, but all possible results are to be realized in distinct universes. Universes continually appear, growing exponentially in number with measurements.

General principles for a such an approach to quantum mechanics were given by DeWitt: (1) the mathematical formalism of quantum mechanics is sufficient as it stands. No metaphysics needs to be added to it [*sic*]; (2) it is unnecessary to introduce external observers or to postulate the existence of a realm where the laws of classical physics hold sway; (3) it makes sense to talk about a state-vector for the whole universe; (4) this state-vector never collapses, and hence the universe as a whole is rigorously deterministic; (5) the ergodic properties of laboratory measuring instruments, although strong guarantors of the internal consistency of the statistical interpretation of quantum mechanics, are inessential to its foundations; (6) the statistical interpretation need not be imposed a priori. Principle (2), that witnessed measurement outcomes are representable within this universal wave-function, removes any dependence of objects on the mental, as required by realism. The known universe is that in which observed data is identical for observing agents; it is one among the 'universes' which, strongly understood (i.e., the wave function representing an objective (sub)universe, universes being distinguished by (differing) eigenstate values), would become infinite in number (cf. [16], Sect. 3.5).

The fullest application of the many-worlds approach to quantum physics has been to quantum cosmology: "Indeed, it is rather difficult to think of any interpretation of quantum cosmology that does not invoke this view in one way or another" ([60], p, 183). Some have considered a more limited ontology in conjunction with the relative state—taking on board only the state of one world (the relative state). For example, Jeffrey Bub has argued that the collapse-free approach to the quantum state can form the basis of a new orthodox interpretation: "This 'new orthodoxy' weaves together several strands: the physical phenomenon of environment-induced decoherence, elements of Everett's relative-state formulation of quantum mechanics, popularized as the 'many worlds' interpretation, and the notion of 'consistent histories' developed by Griffiths and extended in different ways..." ([58], pp. 212-213).[9]

3 Experimental approaches to ontological questions

The development of the understanding of quantum theory through the contemplation of formalisms, states, associated probabilities, and ontologies most compatible with each interpretation, is ongoing. It is also informed by experimentation. The earliest probes of quantum ontology sought to decide whether it was amenable to visualization and, if so, whether quantum objects resemble previously considered posits such as classical corpuscles and waves. Bohr's notion of complementarity seemed to provide a way of coming to terms with the novelty of quantum mechanical system behavior by association with such classical notions, and bolstered the view that quantum mechanics can be considered complete against the EPR argument [42]. And it has been noted that EPR's completeness, rejected by Bohr, is arguably unduly strong because it involves counterfactual events (in their (1) and (I)) involving complementary experimental arrangements.[10] Results of increasingly clever experiments have been accumulating, adding or removing support for competing interpretations and associated ontologies of specific quantum theories.

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[9] As with the Copenhagen approach, there is disagreement among advocates of approaches to quantum theory taking time-evolution as always unitary to quantum ontology. Note also that Bell did not view (at least the Many-worlds version of) the Collapse-Free approach as a solution to the difficulties presented by quantum phenomena, despite its capability of being presented realistically, because he viewed that interpretation as "radically solipsistic," despite contrary claims about it by various advocates (cf. [61], p. 136).

[10] "In the reality assumption the phrase 'can predict' occurs. The phrase...may be understood in the strong sense, that data are at hand for making the prediction, or in the weak sense, that a measurement could be made to provide data for the prediction. EPR assume the weak sense, and indeed unless they did so they could not argue that an element of physical reality exists for all components of spin, those which could have been measured as well as the one that actually was measured...The preference for one rather than the other of these two interpretations of the phrase is not merely a semantical matter...Bohr believed that the concept of reality cannot be applied legitimately to a property unless there is an experimental arrangement for observing it..." [62].

Experimental investigations of property correlations between mutually distant quantum subsystems have been carried out to understand whether quantum mechanics is locally causal. Bell explained local causality as the requirement that "direct causes (and effects) of events are near by, and even the indirect causes (and effects) are no further away than permitted by the velocity of light" [63]. Bell formalized this notion for separated real properties A, B: "Let N denote the specification of all the beables, of some theory, belonging to the overlap of the backward light cones of space-like separated regions 1 and 2. Let Λ be a specification of some beables from the remainder of the backward light cone of 1, and B of some beables in the region 2. Then in a locally causal theory $[p(A|\Lambda, N, B) = p(A|\Lambda, N)]$ whenever both probabilities are given by the theory" [61], Ch. 7. Following Bell's initial, EPR-inspired theoretical work, John Clauser, Michael Horne, Abner Shimony, and Richard Holt (CHSH) sought and derived a similar, directly experimentally testable inequality:

$$|S| \leq 2 \tag{4}$$

where S is a combination of expectation values of four correlated outcomes of measurement events of two distant subsystems; testing it is practicable because perfect correlations between the distant events are not used to derive it [64].[11]

Bell-type inequalities, in effect, encode the strength with which models that might serve as alternatives to standard quantum mechanics that satisfy local causality can provide distant correlations between properties of physical systems. In a local deterministic theory, events are determined by physical law together with the state of affairs in the backward light cone; in a probabilistic theory, the probability of the event cannot be changed by conditioning on events at space-like separation. Events in the two regions may be correlated only due to common causes in accord with Hans Reichenbach's Common-cause principle: Any two correlated events are either causally connected or arise from a common cause. And when correlations are inexplicable in terms of common causes, that is, fail to satisfy this principle, the laws explaining them are called cross-sectional laws [69], p. 4. It was confirmed that $|S| > 2$ can be reached, that is, the CHSH inequality is violated, meaning that there are non-local correlations between subsystem properties; measurements have accorded with the predictions of quantum mechanics [70]. Moreover, several loopholes left open by these results have been progressively removed and violation of the inequality persists, cf., e.g., [71].

In addition to work with photon pairs in Bell-type inequality tests, different experiments have also been designed that work with other elementary particles, or with photons in more subtle apparatus in order to illuminate the quantum ontology better. An example of the last is the delayed-choice experiment introduced by John Wheeler, where the type of measurement made can be selected after the measured object (arguably) enters the apparatus. Such experiments bring the significance of the experimental arrangement, much emphasized by Bohr, into stark relief. In the basic such experiment, photons enter an apparatus which can be quickly switched between two configurations: (1) a simple light-beam splitting system allowing for measurement in one of two paths, and (2) a (Mach–Zehnder) interferometric configuration allowing for (the complementary) measurement of interference visibility.[12] The exact measurement configuration is deferred to a time after some part of the beam could have already entered the apparatus, given the light-speed limit on causal influences. In one configuration, input light first strikes an evenly dividing beamsplitter at and angle of 45°, located at one corner of a rectangle, providing two, orthogonal beam paths; those paths later turn 90° (clockwise for the "high" path, counter-clockwise for the "low" path) at mirrors toward a common region through which they could freely pass at the opposite corner of the rectangle; in each of their two orthogonal directions beyond that region, a single-photon counting photodetector is ready. The detection of energy in a given direction suggests that any photon detected—assuming it must travel along a path—traveled along the path (the "high" or "low") leading into the corresponding detector. In the alternate configuration, a second evenly balanced beamsplitter is located also at the far corner of the path rectangle, allowing for path recombination into both the directions described above instead of free passage. Due to this overlapping coincidence of paths at the second beamsplitter, it is impossible to infer a path a given photon must have traveled, and instead allows a relative-phase determination and self-interference for each photon measured. One "can ask which path does an arriving photon follow—the high road or the low road? That is one choice of question, and the photon detectors stand ready to answer it. To ask for the phase relation between the two beams is a complementary choice of question" [73], pp. 306–307.

Wheeler argued that the clear realizability of such an experiment "shows how wrong it is to say that we are finding out in the one case 'which route' and in the other case the relation of phases in a 'two-route mode of travel.' The world is built in such a way that it denies us the possibility to speak in any well-defined way of 'what the photon is doing' in its travel from point of entry to point of reception" [73], p. 307. The delayed-choice thought experiment was to illustrate Bohrian dictum, "No elementary quantum phenomenon is a phenomenon until it is a registered phenomenon, brought to a close by an irreversible act of amplification." According to Wheeler, "an act of detection is as close as we can get to establishing reality

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[11] Controversy continues to surround the Bell-type inequalities. See, for example, the discussions in [65–67] and of the references therein. It has also been argued that context is essential for the understanding of such expressions, cf., e.g., [68].

[12] For a detailed discussion of associated complementarity relations, see [72].

at the microscopic level.” The counting statistics for an ensemble of photons in this experiment appears to exhibit either particle-like or wave-like behavior conditionally on the final configuration, so that neither of the two sorts of classical characteristic—corpuscular or wave-like—is objectively possessed. Such experiments were carried out and extended by others, for example, Zeilinger who commented that “we brought Wheeler’s thought-experiment into the laboratory and carried it a step further. The idea was to demonstrate that it can be decided after the photon has been registered already whether the phenomenon observed can be understood as a particle or as a wave” [74].

This was done by considering energy–momentum-entangled photons constrained only by their joint energy–momentum, with each having indeterminate values upon creation where, similarly to the EPR situation, the values of both are determined upon the direct measurement of one, regardless of their separation in space and time. What is tested is whether a given one of the photons from those produced pairwise by parametric downconversion has either a determinate path or a determinate momentum upon measurement given that the sort of measurement is arranged after production of the pair. The novelty is that the first of the two photons is detected after the second photon had already itself been detected, so that “whether we obtain the two-slit pattern or not depends on whether the possible position information carried by the other photon has been irrevocably erased or not” [74]. These investigators argued that “while individual events just happen, their physical interpretation ...might depend on the future; it might particularly depend on decisions we might make in the future concerning the measurement performed at some distant spacetime location in the future. It is also evident that the relative spacetime arrangement of the two observations does not matter at all. ...By choosing the apparatus the experimentalist determines whether the phenomenon observed can be seen as a wave or as a particle phenomenon and once the observer has made this choice, Nature gives the respective answer and the other possibility is forever lost. Thus, we conclude, by choosing the apparatus the experimentalist can determine which quality can become reality in the experiment” [74].[13]

What these experiments show is that photons are not classical entities. In such experiments, a property (quality) of a (subatomic) object becomes determinate at the end of the experiment, but not the object’s existence. And Einstein did “not believe that the particle-waves have reality in the same sense as the particles themselves. The wave character of particles and the particle-character of light will—in my opinion—be understood in a more indirect way, not as immediate physical reality” ([43], pp. 373–374). These two characters increasingly appear to be intellectual impositions of classical notions onto quantum systems which do not have these classical characteristics primarily, if at all. And wave-likeness vs. particle-likeness (or other classical likenesses) is less significant (if it ever is at all) at the very smallest spatial scales. Instead, what is of more importance is the question of just which energy-bearing objects exist that the world is made of, in the sense of being decomposable to and/or composable from fundamental quantum entities such as the elementary particles [76].

4 The ontology of quantum field theories

It is remarkable that investigations into the foundations of quantum physics have focused more on measured system properties in relation to the abstract state and probabilities than on the specific object(s) that might bear them. Their general results must cohere with observations on all concrete objects addressed by quantum theory, and experimental investigations into the foundations of quantum theory naturally involve elementary particles. But, so far, only a select few among the many species of elementary particle have been studied in quantum foundations beyond photons [77–79], typically electrically neutral ones which interact minimally between creation and detection, so that the effects of fundamental forces or complexity at higher energies that might render experimental analysis very difficult have been avoided. It is, therefore, of particular importance to consider particle physics—wherein the whole ‘zoo’ of particles is considered, many sorts of particle appear, and intermediate and high energies are present—from a foundational point of view, including its ontological questions.[14] It has become increasingly clear that elementary particles are significantly different from classical particles and that, in the theory best describing them (RQFT), they depend on fields [9]—indeed, their very presence in its fundamental ontology is disputed (cf., e.g., [8, 80–85]).

The quantum theories currently best describing the elementary particles are relativistic field theories (RQFTs). With the arrival of QFT, Pascual Jordan argued for the fundamentality of fields, with both matter and radiation having their sorts of field and particles as mere excitations of them [82]; the idea of the particle as an excitation is prima facie reinforced by the mathematics of raising (creation) and lowering (annihilation) operators acting in the system state space (but see [86]). Indeed, the current field fundamentalist attitude toward quantum field theory (QFT), in which particles

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[13] For a critical assessment of Wheeler’s position on the relation of quantum phenomena to reality, see [75].

[14] Moreover, the character of elementary quantum objects has a decisive influence on the structures found throughout the entire physical world at all of its levels, for example, those of chemistry and biology, because matter can be in specific senses broken down into and constructed from such parts, which are of therefore of great importance. A discussion of this structure and its analysis in relation to space and time can be found in [76].

are thought to reduce to fields, has exploited their calculational convenience (cf. [83]).[15] And relativistically described quantum particles lack the absolute localizability of classical particles. In non-relativistic QFT, with momentum $\{|\vec{k}\rangle\}$ and position $\{|\vec{x}\rangle\}$ bases, one has

$$\hat{\Psi}^\dagger(\vec{x}) = \int d^3\vec{k}((2\pi)^3)^{-1/2}\langle\vec{k}|\vec{x}\rangle a^\dagger(\vec{k}) \tag{5}$$

for a field at the point $\vec{x}$; $a^\dagger(\vec{k})$ "creates" a field excitation with momentum $|\vec{k}\rangle$, where $\langle\vec{k}|\vec{x}\rangle = \exp[-i\vec{k}\cdot\vec{x}]$, and $\hat{\Psi}^\dagger(\vec{x})$ corresponds to the value of the field in space at one moment, a raising operator for the number of quanta located precisely at $\vec{x}$, in that $|\vec{x}\rangle = \hat{\Psi}^\dagger(\vec{x})|0\rangle$. But, in (representative Klein–Gordon) RQFT, although one similarly has

$$\hat{\Psi}^\dagger(\vec{x}) = \int d^3\vec{k}((2\pi)^3\omega(\vec{k}))^{-1/2}\langle\vec{k}|\vec{x}\rangle a^\dagger(\vec{k}) \tag{6}$$

in that case there exists no Hermitian operator serving to indicate position by having eigenvectors $|\vec{x}\rangle$ with eigenvalues $\vec{x}$ over the space. The frequency-dependent term indicates a failure of the orthonormality of $\{|\vec{x}\rangle\}$, so that a quantum described by $|\vec{x}\rangle$ is no longer localized when in such a state.

T. D. Newton and Eugene Wigner suggested instead identifying the mutually orthogonal states

$$|\vec{x}\rangle = \int d^3\vec{k}(2\pi)^{-3/2}\exp[-i\vec{k}\cdot\vec{x}]|\vec{k}\rangle \tag{7}$$

as those with spatial localization. However, such states are not Lorentz invariant [89]: An observer in a different inertial reference frame from that in which the particle is localized about $\vec{x}$ at a time t will see this state as having a non-zero probability of detection arbitrarily far away; similarly, for non-zero times after an initial localization, there is a non-zero probability of detection arbitrarily far away. This runs contrary to intended notion of localization, and is also inadequate. Solutions to the localization question have been sought via unsharp localization operators, cf. [90] and references therein. In particular, Paul Busch et al. investigated the use of positive operator valued measures (POVMs) for this purpose, finding that (1) two (discrete) unsharp as well as sharp observables in important special cases commute if and only, if for any state, the statistics of a measurement of one is unaffected by a nonselective Lüders measurement of the other, and (2) local commutativity of localization observables implies that they are unsharp but only (undesirably) in a strong sense.[16] Among the additional things distinguishing the elementary particles of RQFT is that, unlike the case of classical massive particles, for example, "Electrons can be created and annihilated; their number is not constant; they are not 'elementary' in the original meaning of the word" [11]. With the appearance of RQFT, it was declared that "the days of fixed particle numbers are over. Particles must be considered as the quanta of a field, just as photons are the quanta of the electromagnetic field; such quanta are created or destroyed. The theory of the interaction of charged particles with the radiation field has become a field theory, a theory in which two (or more) quantized fields interact: the matter field(s) and the radiation field" [92], pp. 66–67.

The growth of the observed 'particle zoo' has drawn additional attention to particle ontology since these early theoretical investigations. According to Heisenberg, particles appear in RQFT because "there are physical properties that can be characterized by quantum numbers, for instance angular momentum and electric charge; these quantum numbers may assume positive or negative values, are subject to laws of conservation," and are found together in units [11]. These fundamental quantities appear in specific combinations in particles, which may cease to exist, be replaced or annihilated, and (collectively) reflect their joint conservation. Weinberg characterized the quantum particles as follows. "The so-called elementary particles [of the Standard Model], like photons and quarks and electrons, are 'quanta' of the fields—bundles of the fields' energy and momentum" [93], pp. 59–60. But being readily measurable entities, elementary particles are also likely to persist in physics, even if the fields of RQFT are later not considered fundamental or don't appear in successor theories,[17] And, ultimately, the quantum-of-field notion of the particle is inadequate because it applies strictly only in entirely interaction-free situations [86, 95].

Max Born argued that the set of invariant properties, including those pointed out by Wigner [96], indicate the

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[15] Some realist philosophers, noting that only certain mathematical structures in physical theory appear to remain entirely unchanged as physics has developed, have taken the position of ontological structural realism, according to which mathematical structures are ontologically prior to physical ones, and even to quantum fields that have been considered by some as prior to particles. See [87, 88].

[16] Busch subsequently found that local commutativity is a necessary consequence of Einstein causality for unsharp measurements as well as for sharp measurements as long as they admit local measurements [90, 91].

[17] The elementary particle is found at the very foundation of the notion of the relativistic quantum system, as Weinberg explains regarding his own portrayal QFT: "I start with particles...because what we know about particles is more certain more directly derivable from the principles of quantum mechanics and relativity. If it turned out that some physical system could not be described by a quantum field theory, it would be a sensation; if it turned out that the system did not obey the rules of quantum mechanics and relativity, it would be a cataclysm. In fact, lately there has been a reaction against looking at quantum field theory as fundamental ...From this point of view...the reason our field theories work so well is not that they are fundamental truths, but that any relativistic quantum theory will look like a field theory when applied to particles at low energy" [93] 1–2; also see [94] 15, 85.

presence of a real particle. "The main invariants are called charge, mass (or rather: rest mass), spin, etc.; and in every instance, when we are able to determine these quantities, we decide we have to do with a definite particle. I maintain that we are justified in regarding these particles as real in a sense not essentially different from the usual meaning of the word" [97]. The reality of elementary particles in accord with Born's position has recently been newly argued for [84, 86, 98]. There, a quantum particle is represented by a corresponding irreducible unitary projective representation of the Poincaré group of space-time transformations of a system's putative (free) states and characterized by corresponding group (Casimir) invariant values, which in turn correspond to its values of the physical properties of mass m and (total) spin s [96].[18] The specific compresences of invariant properties found are taken to define the particles in all circumstances, including during interactions when the field-excitation notion fails [84].[19] It is argued that with this extension the elementary particles are seen to coexist with fields but are not reducible to them, i.e., particles are elements of the RQFT ontology along with fields, that the fundamental quantities in their specific combinations in particles are jointly conserved, and that the collection of particles over which they are distributed reflect that conservation over processes in which particles come and go out of existence [98].

Specifically, in RQFT, the states $|p,\, \sigma\rangle$ associated with the motion of a single particle with energy-momentum p and helicity (spin component along the direction of motion) σ (where $P^\mu|p,\, \sigma\rangle = p^\mu|p,\, \sigma\rangle$) transform under the Poincaré group (for particles of positive mass and spin j) as

$$\begin{aligned} U(1,\, a)|p,\, \sigma\rangle &= e^{-iP\cdot a}|p,\, \sigma\rangle = e^{-ip\cdot a}|p,\, \sigma\rangle \\ U(\Lambda,\, 0)|p,\, \sigma\rangle &= \sqrt{(\Lambda p)^0/p^0}\sum_{\sigma'} D^{(j)}_{\sigma'\sigma}(W(\Lambda,\, p))|\Lambda p,\, \sigma'\rangle \end{aligned}$$

respectively, where $j,\, j+1,\, \ldots,\, -j$ are the possible values of σ, $W(\Lambda,\, p) = L^{-1}(\Lambda p)\Lambda L(p)$ is the Wigner rotation, $D^{(j)}_{\sigma'\sigma}(W(\Lambda,\, P))$ are the $2j+1$-dimensional unitary matrices representing the rotation group, and W^μ_ν are the transformations leaving p^μ invariant (cf., e.g., [93]). There are two joint Casimir invariants m, s of the Poincaré group which correspond to the fixed mass and spin of each type of particle, respectively; $P_\mu P^\mu = -m^2$ and $W_\mu W^\mu = -m^2\sigma(\sigma+1)$, where P^μ are the space-time translation-group generators and $W_\mu = -\frac{1}{2}\epsilon_{\mu\nu\rho\sigma}J^{\nu\rho}P^\sigma$ are the generators of the above Lorentz group of transformations of these states, the $J^{\mu\nu}$ being the generators of rotations (cf., e.g., [99], Sect. 2.7).

The requirement for such a quantum system to be elementary is that "there must be no relativistically invariant distinction between the various states" of an individual system [89] for, if there were any such relativistically invariant subspaces, then the system could contain some smaller identifiable subsystem and fail to be elementary. The elementary particle can, therefore, be understood as an irreducible unit of characteristic, compresent properties comprising, at least, rest mass m and spin/helicity s, which are the physical properties corresponding to the invariants under the transformations of this group, and (at least) energy-momentum. The consistency of such a particle with a corresponding field is a consequence of Noether's theorem implying that the required conserved quantities are present when there is symmetry with respect to transformations that are continuous, such as are those of the Poincaré group transformations of a relativistic quantum field in space-time. The energy–momentum (tensor) integrated over space provides the conserved total energy and total momentum in the corresponding volume, and this conservation means that when these change, they flow locally; similarly, symmetry under Lorentz boost implies a local flow of conserved angular momentum. Each quantum field possesses conserved "base properties" B on which the set of conserved properties A of the particle supervenes (for supervenience, cf. [100] passim, and for the quantum particle case, cf. [98], Section 5). Among the base properties B, in addition to the properties of mass, spin, and charge, are field momentum and energy which are integrals of their densities over the volumes considered (cf., e.g., [101], Sect. 12.5).

The characteristic particle properties constituting A are accountable collectively, including when the particles may come into and go out of existence. The sets B and A include common properties but these are sometimes valued differently: In particular, because the field energy–momentum, defined and indexed by space-time point in RQFT, is strictly conserved, the mass-like term which appears in the field propagator for any interacting field differs from the fixed value of mass m_{rest} for the corresponding particle. Thus, the reduction of particles to fields is precluded [98]. Because particles as considered in this approach are related to fields by supervenience rather than being reduced, particles appear in the fundamental RQFT ontology along with fields.

5 Conclusion

The investigation of the ontology of quantum theory has involved theoretical study, conceptual analysis, and experimentation. The EPR investigation of the quantum mechanics of composite systems and Bohr and Heisenberg's response to it first showed the significance of ontology for the understanding of quantum physics and vice versa. Different ontologies for quantum physics have since been considered, from one where object properties are more or less indefinite in the universe, say, in the ontology of Heisenberg's later interpretation, to an

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[18] And the allowed (discrete) spin values are integral (permutation-symmetric) or half-integral (permutation anti-symmetric).

[19] That failure was shown in [95].

expanding multitude of equally real universes wherein all possible property values are realized in the many-worlds ontology. It is evident that the approach to quantum principles and epistemological requirements taken by the theorist can have a strong influence on which ontology is judged to accord best with a physical theory in conjunction with related experimental results. Thus far, these together have favored ontologies where subatomic objects may have classically inexplicable, indefinite non-local correlated properties. One is witnessing the progress of experimental metaphysics.

Because experiments designed to illuminate the foundations of quantum theory have involved relatively simple and weakly interacting systems at low energies, the higher-energy realms, where relativistic quantum field theory is required, now lie at its frontier, where the relationship between elementary particles and fields is a central ontological question. It has been shown that, on one compelling understanding of the notion, for realists, elementary particles are required ontological elements along with quantum fields because these particles supervene on fields rather than reducing to them. Similarly, investigations of quantum information processing technology may provide additional important information helpful for the clarification of the ontological structure of quantum theory because these technologies also depend on the utilization of quantum behavior in relatively more complex mesoscopic systems.

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References

1. T.S. Kuhn, *The Structure of Scientific Revolutions* (University of Chicago Press, Chicago, 1962)
2. J.Z. Buchwald, *From Maxwell to Microphysics* (University of Chicago Press, Chicago, 1985)
3. A. Einstein, On the Ether, in *The Philosophy of Vacuum*. ed. by S. Saunders, H. Brown (Oxford University Press, Oxford, 1991)
4. E. Schrödinger, *Collected Papers on Wave Mechanics, Transl. by J. F. Shearer* (Chelsea, New York, 1927)
5. F.A. Muller, The equivalence myth of quantum mechanics-part I. Stud. Hist. Philos. Sci. B **28**, 35–61 (1997)
6. J. Von Neumann, *Mathematical Foundations of Quantum Mechanics* (Princeton University Press, Princeton, 1955). (**English translation of Mathematische Grundlagen der Quantenmechanik. Berlin: Springer (1932)**)
7. A. D'Abro, *The Rise of the New Physics* (Dover, London, 1951)
8. S. Saunders, Are quantum particles objects? Analysis **66**, 52–63 (2006)
9. E. Castellani (ed.), *Interpreting Bodies* (Princeton University Press, Princeton, 1998)
10. S. Cowling, Haecceitism, in *The Stanford Encyclopedia of Philosophy* edited by E.N. Zalta, U. Nodelman (Spring, 2023 Edition). https://plato.stanford.edu/archives/spr2023/entries/haecceitism/
11. W. Heisenberg, The nature of elementary particles. Phys. Today **29**, 32 (1976)
12. C.A. Fuchs, A. Peres, Quantum theory needs no interpretation. Phys. Today **53**, 70 (2000)
13. W.M. Dickson, *Quantum Chance and Non-locality* (Cambridge University Press, Cambridge, 1998)
14. M. Devitt, *Realism and Truth* (Princeton University Press, Princeton, 1984)
15. G. Bacciagaluppi, O. Darrigol, T. Hartz, C. Joas, A. Kojevnikov, O. Pessoa Jr., O. Freire Jr., *The Oxford Handbook of the History of Quantum Interpretations* (Oxford University Press, Oxford, 2022)
16. G. Jaeger, *Entanglement, Information, and the Interpretation of Quantum Mechanics* (Springer, Heidelberg, 2009)
17. W. Heisenberg, The Development of the Interpretation of the Quantum Theory, in *Niels Bohr and the Development of Physics, Essays Dedicated to Niels Bohr on the occasion of his seventieth birthday*. ed. by W. Pauli et al. (Pergamon Press Ltd., London, 1955)
18. P.A.M. Dirac, *The Principles of Quantum Mechanics* (Clarendon Press, Oxford, 1930)
19. K. Popper, *Quantum Theory and the Schism in Physics* (Rowman and Littlefield, Towata, 1982)
20. H. Everett, III "On the Foundations of Quantum Mechanics" (Ph. D. thesis, Princeton University, 1957)
21. H. Everett III., 'Relative State' formulation of quantum mechanics. Rev. Mod. Phys. **29**, 454 (1957)
22. H. Everett III., The theory of the universal wave function, in *The Many-Worlds Interpretation of Quantum Mechanics*. ed. by B.S. DeWitt, N. Graham (Princeton University Press, Princeton, 1973), p.3
23. A. Einstein, B. Podolsky, N. Rosen, Can quantum-mechanical description of physical reality be considered complete? Phys. Rev. **47**, 777 (1935)
24. E. Schrödinger, Discussion of probability relations between separated systems. Proc. Camb. Philos. Soc. **32**, 446 (1935)
25. K. Przibram (ed.), *Letters on Wave Mechanics* (Philosophical Library, New York, 1967)
26. H. Krips, *The Metaphysics of Quantum Theory* (Oxford University Press, Oxford, 1987)
27. D. Khlentzos, Challenges to metaphysical realism, in *The Stanford Encyclopedia of Philosophy* edited by E.N. Zalta (Spring, 2021 Edition). https://plato.stanford.edu/archives/spr2021/entries/realism-sem-challenge/
28. S. Gudder, P. Lahti, Paul Busch: at the heart of quantum mechanics. Found. Phys. **49**, 457 (2019)
29. A. Allahverdyan et al., A sub-ensemble theory of ideal quantum measurement processes. Ann. Phys. **376**, 324 (2017)
30. A. Auffèves, P. Grangier, Revisiting Born's rule through Uhlhorn's and Gleason's theorems. Entropy **24**, 199 (2022)
31. A. Auffèves, P. Grangier, Recovering the quantum formalism from physically realist axioms. Sci. Rep. **7**, 43365 (2017)
32. E. Schrödinger, Quantisierung als Eigenwertproblem. Ann. Phys. (Berlin) **81**, 109 (1926). (**English summary in Phys. Rev. 28, 1049-1070 (1926)**)

33. I. Bengtsson, K. Zyczkowski, *Geometry of Quantum States* (Cambridge University Press, Cambridge, 2006)
34. G. Jaeger, *Quantum Information* (Springer, New York, 2007)
35. A. Einstein, Remarks to the Essays Appearing in this Collective Volume, in *Albert Einstein: Philosopher-scientist (The Library of Living Philosophers, Volume 7, Part II)*. ed. by P.A. Schilpp (Open Court, Evanston, 1949), p.663
36. G. Jaeger, What in the (quantum) world is macroscopic? Am. J. Phys. **82**, 896 (2015)
37. G. Jaeger, Quantum contextuality in the Copenhagen approach. Philos. Trans. R. Soc. A **377**, 20190025 (2019)
38. G. Jaeger, Quantum contextuality and indeterminacy. Entropy **22**, 867 (2020)
39. D. Bohm, Y. Aharonov, Discussion of experimental proof for the paradox of Einstein, Rosen and Podolsky. Phys. Rev. **108**, 1070 (1957)
40. A. Shimony, Controllable and uncontrollable nonlocality, in *Foundations of Quantum Mechanics in Light of the New Technology*. ed. by S. Kamefuchi et al. (Physical Society of Japan, Tokyo, 1983), p.225
41. A. Einstein, Autobiographical notes, in *Albert Einstein: Philosopher-scientist (The Library of Living Philosophers, Volume 7, Part I)*. (Open Court, Evanston, 1949), p.1
42. N. Bohr, Can the quantum-mechanical description of reality be considered complete? Phys. Rev. **48**, 696 (1935)
43. J. Stachel, Einstein and the quantum: fifty years of struggle, in *From Quarks to Quasars*. ed. by R.G. Colodny (Univ. Pittsburgh Press, Pittsburgh, 1986), p.349
44. A. Shimony, Experimental test of local hidden variable theories, in *Foundations of Quantum Mechanics*. ed. by B. d'Espagnat (Academic, New York, 1971)
45. B. d'Espagnat (ed.), *Foundations of Quantum Mechanics* (Academic, New York, 1971)
46. E.G. Beltrametti, C. Cassinelli, A. Shimony, The logic of quantum mechanics. Phys. Today **36**, 62–64 (1983)
47. J.S. Bell, On the problem of hidden variables in quantum mechanics. Rev. Mod. Phys. **38**, 447 (1966)
48. F.J. Belinfante, *A Survey of Hidden-Variable Theories* (Pergamon, Oxford, 1973)
49. H.P. Robertson, The uncertainty principle. Phys. Rev. **34**, 163 (1929)
50. G. Jaeger, Quantum unsharpness, potentiality, and reality. Found. Phys. **49**, 663 (2019)
51. G. Jaeger, Quantum potentiality revisited. Philos. Trans. R. Soc. A **375**, 20160390 (2017)
52. P. Busch, G. Jaeger, Unsharp quantum reality. Found. Phys. **40**, 1341 (2010)
53. H.J. Folse, *The Philosophy of Niels Bohr* (North-Holland, Amsterdam, 1985)
54. G. Jaeger, A realist view of the quantum world. Act. Nerv. Super. (Special Issue for Henry Stapp) **61**, 51 (2019)
55. P.C.W. Davies, J.R. Brown (eds.), *The Ghost in the Atom* (Cambridge University Press, Cambridge, 1986)
56. G. Jaeger, D. Simon, A.V. Sergienko, D. Greenberger, A. Zeilinger (eds.), *Quantum Arrangements* (Cham, Springer Nature, 2021)
57. M. Zukowski, C. Brukner, Bell's theorem for general N-qubit states. Phys. Rev. Lett. **88**, 210401 (2002)
58. J. Bub, *Interpreting the Quantum World* (Cambridge University Press, Cambridge, 1997)
59. B.S. DeWitt, N. Graham, *The Many-Worlds Interpretation of Quantum Mechanics* (Princeton University Press, Princeton, 1973)
60. C. Isham, *Lectures on Quantum Theory: Mathematical and structural foundations* (Imperial College Press, London, 1995)
61. J.S. Bell, *Speakable and Unspeakable in Quantum Mechanics* (Cambridge University Press, Cambridge, 1987)
62. D.M. Greenberger, M.A. Horne, A. Shimony, A. Zeilinger, Bell's theorem without inequalities. Am. J. Phys. **58**, 1131 (1990)
63. M. Bell, K. Gottfried, M. Veltman, S. John (eds.), *Bell on the Foundations of Quantum Mechanics* (World Scientific, Singapore, 2001)
64. J.F. Clauser, M. Horne, A. Shimony, R.A. Holt, Proposed experiments to test local hidden-variable theories. Phys. Rev. Lett. **23**, 880 (1973)
65. M. Kupczynski, EPR paradox, quantum nonlocality and physical reality. J. Phys. Conf. Ser. **701**, 012021 (2016)
66. R.D. Gill, Gull's theorem revisited. Entropy **24**, 679 (2022)
67. R.D. Gill, Kupczynski's contextual locally causal probabilistic models are constrained by Bell's theorem. Quantum Rep. **5**, 481 (2023)
68. T. Nieuwenhuizen, M. Kupczynski, The contextuality loophole is fatal for Bell inequalities. Found. Phys. **47**, 316 (2017)
69. H. Reichenbach, *Philosophic Foundations of Quantum Mechanics* (University of California Press, Berkeley, 1944)
70. A. Aspect, Trois tests expérimentaux des inegalités de Bell, Ph. D. thesis (Université Paris-Sud, PhD thesis no. 2674, Paris, 1983)
71. J. Handsteiner, A.S. Friedman, D. Rauch, J. Gallicchio, B. Liu, H. Hosp, J. Kofler, D. Bricher, M. Fink, C. Leung, A. Mark, H.T. Nguyen, I. Sanders, F. Steinlechner, R. Ursin, S. Wengerowsky, A.H. Guth, D.I. Kaiser, T. Scheidl, A. Zeilinger, Cosmic Bell test: measurement settings from Milky Way Stars. Phys. Rev. Lett. **118**, 060401 (2017)
72. G. Jaeger, A. Shimony, L. Vaidman, Two interferometric complementarities. Phys. Rev. A **51**, 54 (1995)
73. J.A. Wheeler, How come the quantum? Ann. NY Acad. Sci. **480**, 304 (1986)
74. A. Zeilinger, Why the Quantum? "It" from "Bit"? A participatory universe? Three far-reaching challenges from John Archibald Wheeler and their relation to experiment, in *Science and Ultimate Reality*. ed. by J.D. Barrow et al. (Cambridge University Press, Cambridge, 2004), pp.201–220
75. G. Jaeger, On Wheeler's meaning circuit, in *A Quantum-Like Revolution*. ed. by A. Plotnitsky, E. Haven (Springer-Nature, Cham, 2023)
76. G. Jaeger, *Quantum Objects* (Springer, Heidelberg, 2014)
77. A. Go, Observation of Bell inequality violation in B mesons. J. Mod. Opt. **51**, 991 (2004)

78. Y. Hasegawa, R. Loidl, G. Badurek, M. Baron, H. Rauch, Violation of a Bell-like inequality in single-neutron interferometry. Nature **425**, 45 (2003)
79. J. Li, C.-F. Qiao, Feasibility of testing local hidden variable theories in a Charm factory. Phys. Rev. D **74**, 076003 (2006)
80. P.C.W. Davies, Particles do not exist, in *Quantum Theory of Gravity: Essays in Honor of the 60th Birthday of Brice DeWitt*. ed. by S.M. Christensen (Hilger, Bristol, 1984), pp.66–77
81. M. Redhead, A philosopher looks at quantum field theory, in *Philosophical Foundations of Quantum Field Theory*. ed. by H. Brown, R. Harré (Oxford University Press, Oxford, 1988)
82. M. Born, W. Heisenberg, P. Jordan, Zur Quantenmechanik, II. Zs. Phys. **35**, 557–615 (1926)
83. T. Fox, Haunted by the spectre of virtual particles. J. Gen. Philos. Sci. **39**, 35–51 (2008)
84. G. Jaeger, Exchange forces in particle physics. Found. Phys. **51**, 13 (2021)
85. A. Plotnitsky, Something happened. Eur. Phys. J. Spec. Top. **230**, 881–901 (2021)
86. G. Jaeger, Are virtual particles less real? Entropy **21**, 141 (2019)
87. A. Bokulich, P. Bokulich, *Scientific Structuralism* (Springer, Dordrecht, 2011)
88. J. Saatsi, S. French (eds.), *Scientific Realism and the Quantum* (Oxford University Press, Oxford, 2020)
89. T.D. Newton, E. Wigner, Localized states for elementary systems. Rev. Mod. Phys. **21**, 400 (1949)
90. P. Busch, M. Grabowski, P.J. Lahti, *Operational Quantum Physics* (Springer, Berlin, 1995)
91. G. Jaeger, Localizability and elementary particles. J. Phys. Conf. Ser. **1638**, 012010 (2020)
92. J. Schwinger, Renormalization theory of quantum electrodynamics: an individual view, in *The Birth of Particle Physics*. ed. by L. Brown, L. Hoddeson (Cambridge University Press, Cambridge, 1983), pp.329–353
93. S. Weinberg, *The Quantum Theory of Fields*, vol. 1 (Cambridge University Press, Cambridge, 1995)
94. R.P. Feynman, *QED* (Princeton University Press, Princeton, 1985)
95. D. Fraser, The fate of ‘Particles’ in quantum field theories with interactions. Stud. Hist. Philos. Sci. B **39**, 841–859 (2008)
96. E. Wigner, On unitary representations of the inhomogeneous Lorentz group. Ann. Math. **40**, 149–204 (1939)
97. M. Born, Physics in the last fifty years. Nature **168**, 625 (1951)
98. G. Jaeger, The particles of quantum fields. Entropy **23**, 1416 (2021)
99. L.H. Ryder, *Quantum Field Theory*, 2nd edn. (Cambridge University Press, Cambridge, 1996)
100. E. Savellos, Ü. Yalçin, *Supervenience: New Essays* (Cambridge University Press, Cambridge, 1995)
101. A. Duncan, *The Conceptual Framework of Quantum Field Theory* (Oxford University Press, Oxford, 2012)