PHILOSOPHY OF PHYSICS

The Foundations of Quantum Mechanics in the Philosophy of Nature

By Grete Hermann

Translated from the German, with an Introduction, by Dirk Lumma

THE FOLLOWING ARTICLE BY GRETE HERMANN ARGUABLY *occupies an important place in the history of the philosophical interpretation of quantum mechanics. The purpose of Hermann's writing on natural philosophy is to examine the revision of the law of causality which quantum mechanics seems to require at a fundamental level of theoretical description in physics. It is Hermann's declared intention to show that quantum mechanics does not disprove the concept of causality, "yet has clarified [it] and has removed from it other principles which are not necessarily connected to it."*[1] *She attempts to show that this most "obvious" counter-example to the aprioricity of causality, quantum theory, is in fact not a counter-example at all.*

The central claim of Hermann's essays published in the 1930s[2] *implies that quantum mechanics, "though predictively indeterministic, is retrodictively a causal theory."*[3] *In her argument, Hermann commits to the orthodox formulation of quantum mechanics characterized in Bohr's early essays*[4]*: the quantum postulate, the idea that all observations "disturb" the object system, the framework of complementarity, and the requirement that the observing agency be described by means of classical concepts. From today's point of view, Hermann's essays must also be considered part of the debate about the completeness of the quantum mechanical description. For if she succeeds, she will have rejected all those approaches as futile which aim to revise quantum theory on the basis of additional parameters in order to reinstate the predictability of specific experimental outcomes.*

In 1935, Bohr introduces a relational approach to quantum theory in his response[5] *to the challenge by Einstein, Podolsky, and Rosen.*[6] *There, Bohr relativizes quantum phenomena with respect to a kind of apparatus, to an experimental framework of certain general characteristics. In her essays, Hermann proposes a form of relationalism that goes much further than Bohr's. For her, quantum mechanical phenomena are not only relative to the experimental framework of observation, the* Beobachtungszusammenhang, *but also relative to the concrete particular of the specific outcome of the observation, the* Beobachtung. *Such a notion of relativization to a concrete particular is a key feature of Everett's formulation of quantum mechanics,*[7] *proposed in 1957. Everett introduces a formal relativization procedure between quan-*

Dirk Lumma is a graduate student in philosophy and physics at the Massachusetts Institute of Technology.

tum states, and many philosophers and physicists have used his formalism as the basis for metaphysically more explicit interpretations. Among these are DeWitt,[8] *Albert and Loewer,*[9] *Lockwood,*[10] *and Saunders,*[11] *to name only a few. A more recent article discussing a relational interpretation of quantum mechanics was published in this journal three years ago.*[12]

There have been many critical responses to Hermann's articles,[13] *arguing mostly that her notion of relativization to specific experimental outcomes seems futile since it does not adequately serve the purpose for which it was invented. Historically speaking, Hermann nonetheless forms the missing link between the early Bohr, where the classical observer interacts with the quantum system, and Everett's framework, where the observer is fully described in quantum mechanical terms, and where the* Beobachtung *is expressed by the quantum state that is Everett-relative to the observer state after the completion of a measurement. Hermann's position should be seen as intermediate between these two extreme positions, for she combines Bohr's classical observer with a relativization to a concrete particular.*

—D.L.

THE PHYSICAL CONSEQUENCE OF QUANTUM MECHANICS, which casts doubt upon traditional views in the philosophy of nature, especially upon the concept of causality, implies that the predictive calculation of future processes in nature is restricted by a sharp, insurmountable limit. The idea of the Laplacian demon, who has complete knowledge of the present state of nature, who oversees all laws of nature, and who can predict the future course of events on the basis of this knowledge, therefore loses all application to nature. And yet this idea merely expressed the conviction that each process in nature is in all its characteristics caused by previous events and must thus be predictable from these causes by someone knowledgeable of the laws of nature. Doubt is cast upon the belief in the unlimited possibility of such [predictive] calculations, and thus also upon the universal causal connection among events in nature.

The experimental basis for the considerations which culminate in the assertion of insurmountable limits to predictive calculations is given in the so-called dualism experiments. According to them, the classical distinction between radiative processes which involve the fast motion of small massive particles and those [processes] in which a wave is evolving becomes inapplicable. In classical physics, α– and β–rays, which are emitted by radioactive elements, were considered matter beams since they leave line-like traces when passing through saturated water vapor, for example, thereby demonstrating the discrete character of moving particles. The same rays, however, lead to interference effects after having passed through or having been reflected by a grating, and thus force upon the scientist the assumption of dealing with a wave. In a similar way, the light rays, which have been unambiguously interpreted as wave evolutions since the discovery of the interference effects, have exhibited properties that indicate their corpuscular nature.

Quantum mechanics does justice to these experiments by assuming that each atomic process must *also* be describable in the wave picture, each wave process *also* in the corpuscular picture. But given the contrast between these two pictures, one and the same process cannot possibly have both all characteristics of an evolving wave and all attributes of a corpuscular motion. So the compatibility of both pictures is only possible since the one of them limits the applicability of the other.

With the much-quoted uncertainty relations, Heisenberg has exactly calculated the limitations which the wave and particle pictures, applied to the same physical process, impose on each other. The most well-known of [these relations] prohibits, in the particle picture, the simultaneous sharp determination of the position and the momentum of particles: if Δq is the accuracy to which the position, say, of an electron, is given and Δp the accuracy of its momentum determination, then the relation $\Delta q \, \Delta p \geq h$ holds, where h is Planck's constant.

In classical physics, the measurabilities of different quantities are independent of each other. The physical state of a system can therefore be characterized by listing the values of all relevant physical quantities. The quantum-mechanical formalism, in contrast, needs a new type of symbol for the state description which exhibits mutual dependency in the determinability of different quantities.

Due to Bohr's *correspondence principle* these symbols, the wavefunctions of physical systems, and the mathematical formalism providing the calculational rules valid for their use closely follow the classical theory. The classical description is compatible with the quantum-mechanical one as long as its quantities remain undetermined to within an accuracy such that the uncertainty relations are satisfied.

If position and momentum of a particle in principle cannot both be measured with arbitrary accuracy, then how could one gain secure knowledge of the future trajectory, which is just determined by the present position and momentum of the body?

On the other hand, this correspondence goes along with the fact that the quantum-mechanical formalism does not allow one to determine the outcome of a measurement in advance with arbitrary accuracy. Rather it allows us, depending on the wavefunction by which the physical system was characterized before the measurement, only the inference of more or less far-reaching probability statements.

Yet the proof that this formalism offers the basis only for limited predictions does not ensure that the demonstrated limitations are insurmountable. Someone who doubts them need not thereby criticize the formalism itself. It is possible that this formalism will also prove itself in the future, as it has done so far. But what prevents us from assuming that, as our physical knowledge increases, new formulas and rules might be added to it which in combination with the present formal approach might render exact predictions possible again? Everything depends upon the answer to this question.

It suggests itself to read off the impossibility of such an increase [in knowledge] from the uncertainty relations. If position and momentum of a particle in principle cannot both be measured with arbitrary accuracy, then how could one gain secure knowledge of the future trajectory, which is just determined by the present position and momentum of the body?

This argument, however, is based on the view that, regardless of the uncertainty relations, the electron, as a particle in the classical sense, has at any moment in time an exact position and an exactly-determined momentum, through which—leaving aside any external disturbances—its future motion is fixed, and on the opinion that *this cause* of the future physical course [of events] will forever be concealed from observation. The uncertainty relations are therefore interpreted merely subjectively and do not seem to say anything about the nature of the physical systems [described].

This subjective interpretation is incompatible with the derivation of these relations from the dualism of wave and particle pictures: by *also* subjecting each atomic process to the characteristics of the wave picture, one restricts the application of the corpuscular picture in such a way that not all characteristics of moving point masses—in the classical sense—can be properties of the moving electron as well.

But if according to this reasoning the electron does not simultaneously have an exact position and an exact momentum, then its exact position and its exact momentum cannot be decisive for its further motion. Having dropped this assumption, it becomes an open question whether one could not find other characteristics[14] upon which the course of the motion depends and from which one could calculate it in advance. The formalism of quantum mechanics does not acknowledge such characteristics. From that, however, it does not follow that one is justified to declare them impossible.

Discussions of numerous other attempts to prove the limitations of predictive calculability as in principle insurmountable lead to similar considerations. All these arguments do exhibit immense difficulties, which stand in the way of any attempt to overcome the limitations of predictive calculability. But they leave open the decisive question: there are indeed measurements in each quantum-mechanically characterized state of a physical system whose outcome cannot be predicted on the basis of knowing this state. But why should the otherwise common procedure in physics be blocked off, viz. to search for new characteristics, to refine the state description of physical systems by means of them, and to find in them the determinant for the previously non-predictable measurement outcome?

There can only be a single sufficient reason to renounce as fundamentally futile any further search for the causes of an observed process: that one already knows these causes.

Someone who flatly denies the possibility of such [new] characteristics comes into conflict with the principle of the incompleteness of experience. There is no other criterion for having recognized all characteristics significant to a [certain] realm of nature except for the possibility of being able to understand all processes belonging to this realm in light of their accordance with [natural] law. Whether one has recognized these interrelations within natural law can be seen from one's ability to derive predictions from them which prove themselves empirically correct.

Therefore, there can only be a single sufficient reason to renounce as fundamentally futile any further search for the causes of an observed process: *that one already knows these causes.*

Consequently, the theory of quantum mechanics, asserting that the calculative prediction of measurement outcomes will always be limited, is faced with the following dilemma. Either [the theory] itself provides the causes which completely determine the outcomes of measurements—how could it then forbid the scientist to search for these causes in a particular case and to calculate the measurement outcome from them in advance? Or else [the theory] does not provide these causes—how could it then exclude the possibility of discovering these causes in the future without arbitrarily anticipating the inquiry into unknown realms of natural science?

The quantum mechanical formalism contains a way out of this dilemma. The solution of the difficulties is already hinted at by Bohr's correspondence principle. This principle permits and requires us to take every consequence which follows classically from the characterization of the given circumstances also as the basis for the quantum-mechanical *Ansätze*, provided the classical concepts are employed within their appropriate realm of applicability in quantum mechanics.

In certain cases of courses of events which cannot be predictively calculated by means of quantum mechanics, just this analysis, from the point of view of correspondence, provides exact information on those physical determinants upon which these courses of events are dependent with respect to all their relevant characteristics. Those are the cases in which such a course of events belongs to a measurement process and also serves to establish a connection from the observed object to the measurement apparatus.

The possibility of finding new characteristics which strictly determine the outcome of a measurement is indeed precluded in quantum mechanics.

Consider the case of a measurement apparatus indicating the result of a measurement through the position of a pointer; the step from reading this pointer position to the quantum-mechanical *Ansatz* for the state of the observed physical system then presupposes a theory of interaction between system and measurement apparatus. This theory is solely founded on the classical concepts and shows by means of them whether and to what extent the deflection of the pointer is conditioned by the state of the object of measurement and [to what extent it] thus provides grounds for the determination [of the state]. The application of any electrical or optical instrument, [or] any scale is therefore based on a retrodictive conclusion from the measurement apparatus to the object of measurement. In this retrodictive conclusion the pointer position of the measuring apparatus is explained as the necessary effect which was forced upon the instrument by the system to be measured during the measurement procedure.

If this concerns a measurement whose outcome was not quantum-mechanically predictable, then apparently the same [reasoning] also applies to the pointer position of the measurement apparatus through which the outcome of the measurement is recorded. Yet for this unpredictable course of events the interpretation of the measurement process itself provides the reasons which made it come about. So it would be futile to look for the cause of its occurrence in physical characteristics which research might have failed to notice up to now. *The theory of measurement already has sufficient explanatory reasons available.*

Apparently, the case is not different for the state of the measured system. For it is arbitrary for the course of a natural process whether it is itself regarded as the object of measurement or whether it is of interest to the scientist only as a means of measuring other processes.

The possibility of finding new characteristics which strictly determine the outcome of a measurement is thus indeed precluded in quantum mechanics for the only reason which is sufficient as a proof given the incompleteness of experience: *the characteristics determining the measurement outcome are already provided by quantum mechanics itself.*

That seems peculiar. If quantum mechanics knows how to explain completely the measurement outcome *after* it occurred, why does [the theory] not provide the means to calculate [this outcome] *before* the measurement on the basis of the explanatory reasons that become apparent afterwards?

The solution to this difficulty is again found in the correspondence principle. The predictions which one reaches from the quantum-mechanical characterization of a system cannot go beyond those which can be derived from the classical representations that have limited applicability only. If one nevertheless, *after* having read off the measurement apparatus, explains its unpredictable pointer position by a theory of the measurement process, then this theory traces the process of measurement back to states which were not and could not have been contained in the previous description of object and measurement apparatus. The description of systems in quantum mechanics is therefore not unique, but only shows, as it were, an aspect of a physical system which the scientist can comprehend on the basis of the [specific outcome of] the observation made. Relative to this specific outcome of observation,[15] the system has no sharp values with regard to certain physical quantities and accordingly has no characteristics from which the outcome of a sharp measurement of these quantities could be inferred either. Yet if one carries out such a measurement, which disturbs the system and takes it into another state, then one obtains exact quantum-mechanical statements for the measured quantity and, moreover, reasons for why just this unpredicted value of the measurement had to appear. For a prediction of [this] result these reasons could still not be used; for they determine the system only relative to the precise outcome of observation, which was made in the measurement itself. So beforehand they could not have been available to the physicist for predictive calculations.

This relative character of the quantum-mechanical way of description becomes clearly evident in an instructive thought experiment.[16]

Let the position of an electron be determined only by a [particular] plane; let its location on this plane be unknown. Then, according to the uncertainty relations, only the momentum component lying within the plane can be given; in the direction perpendicular [to the plane], the momentum remains undetermined.

A measurement of the electron position is to be carried out by illumination. The deflected light is [assumed] to pass a microscope and to be absorbed by a photographic plate. For simplicity, we assume that the intensity of the light employed for doing this is reduced such that the entire process involves only a single light quantum. In accordance with the dualism of the wave and particle pictures, this light quantum on the one hand is to be considered as a corpuscle which collides with the electron according to the classical laws of the elastic collision, and on the other hand as a wave which, deflected by the electron, evolves in the microscope according to the classical laws of optics.

The principle of momentum conservation applies to the collision of light quantum and electron: both are deflected in the collision; their momentum changes are opposite and equal.

In order to obtain a focused image of the electron, we place the plate in the microscope's image plane which corresponds to the object plane and where, according to classical theory, all wavelets originating in a point of the object plane are recombined in one point. So we use the classical picture of a spherical wave that expands from the point of collision into all directions and that, insofar as it hits the aperture of the microscope, enters through [the microscope's] lenses. The entire aperture of the microscope is thus involved in this process, and therefore it does not make any sense—now again in the corpuscular picture—to distinguish a particular direction into which the light quantum was reflected by the electron and along which it entered the microscope. It thus follows that the change in momentum which the electron underwent in the collision cannot be determined precisely either. So one will have to characterize the state of the electron immediately after the collision by a wavefunction that describes a sharp position, yet a momentum which is less sharp compared with [the one in] the previous state.

One can be led to different wavefunctions for the same system and at the same moment in time depending on the framework of observation on hand.

One reaches a completely different description of the collision if one does not mount the plate in the image plane, but in the focal plane of the microscope. In this case, too, the plate will show a sharp image, for the light quantum only has enough energy to excite a single atom on the plate. This point of the focal plane hit by the light quantum is characteristic of a particular direction along which the light entered the microscope. The [intuitive] idea of the wave picture, which in this case is used to interpret the observed outcome, is accordingly that of a bundle of parallel rays which are recombined through their refraction in a single point of the focal plane of the lenses. The direction along which the light quantum entered the microscope is therefore fixed; yet the position on the object plane at which it started after the collision with the electron remains undetermined. If the momentum of the light quantum before the collision is known, then its change in momentum is also determined by the direction of the light quantum after the collision; and thus, according to the principle of the conservation of momentum, [the change in momentum] of the electron [is determined] as well. So even though in this case nothing happened to the electron that did not happen in the first case, one now has to characterize its state after the collision by a wavefunction with a blurred position and a relatively sharp momentum.

The juxtaposition of these different possibilities apparently means that one can be led to different wavefunctions for the same system and at the same moment in time—*viz.* for the electron at the time immediately after the collision with the light quantum—depending on the, let us say, framework of observation[17] on hand. The quantum-mechanical characterization is not, like the classical one, attributed to the physical system, as it were, "in itself",[18] i.e., independently of the observations through which one acquires knowledge of it.

What revision of the principle of causality of classical physics has to be made on the basis of this result?

Two points of the preceding considerations are crucial for an answer: the limits of predictive calculability of future events have indeed turned out to be in principle insurmountable; yet there is no course of events for which no causes could be found in the framework of the quantum-mechanical formalism.

Both claims seem to contradict each other. While the first one states that unavoidable limits are set to the application of causal inferences and to the control over nature lent to human beings, the second one emphasizes the in principle unrestricted applicability of causal representations to which every natural process is always subjected with regard to all physical features that characterize it.

The resolution to this conflict can only succeed on the basis of a discussion of those concepts which play a crucial role in the quantum-mechanical results mentioned: the concept of predictive calculability of the course of nature on the one hand and the [concept of] causal connection on the other hand.

We have already touched upon the close connection between both concepts. The explanatory value of a physical hypothesis can only be verified by predictively calculating the future course of events in nature. And without the possibility of such a verification the assertion of causal connections loses the character of scientific knowledge.

This relationship has in many cases wrongly lead to the assumption that one is, strictly speaking, dealing with identical concepts here and that only the linguistic description falsely suggests a distinction. With this interpretation the contradiction between the two quantum-mechanical claims mentioned is unavoidable. If the relation between cause and effect consists of nothing more than the fact that the effect can be predicted when the cause is known, then there exist no causes for events which can in principle not be calculated predictively. Quantum mechanics presupposes and calls upon an explanation based on natural law also for events which are not predictively calculable; this fact therefore shows that equating both concepts is based on a confusion. The causal connection immediately concerns only the necessary sequence of the events themselves. The possibility of calculating them predictively on the basis of understanding causal relationships provides the criterion for the correct application of the concept of causation. Quantum mechanics forces [us] to distinguish both concepts carefully.

Formulated independently of its criterion of applicability, the law of causality states that nothing in nature happens which is not brought about in all its physically determinable characteristics by previous events, that is, which does not succeed them with necessity. In this sense, gapless causality is not only consistent with quantum mechanics, but is demonstrably presupposed by it.

Gapless causality is not only consistent with quantum mechanics, but is demonstrably presupposed by it.

But what about the criterion of causality? Quantum mechanics has to rely on such a criterion as well and extracts it, just as classical physics does, from the possibility of predicting future events. In contrast to classical physics, however, it has dropped the assumption that every causal claim can immediately be tested via the prediction of its effect. Even for events which cannot be calculated in advance, quantum mechanics provides a causal explanation and verifies it via predictions. But this verification is achieved in a [rather] roundabout way: from events which cannot be calculated predictively their cause is inferred retrodictively; and assuming this cause existed, one can then in turn derive predictions of coming events whose occurrence can be verified empirically. In this way the blackening of the plate in the example dealt with is traced back to the collision between electron and light quantum, from which one can infer the electron state that is still accessible to observation.

This new possibility of a merely mediate verification of causal claims has not been taken serious by classical physics; this is due to the fact that the relative character of the quantum-mechanical description of nature is alien to classical physics. For classical physics the characterization of any system is unique and independent of the way in which the observer acquires knowledge of it. And that is why it conclusively reaches the position that, given sufficient experimental resolution and sufficient knowledge of the natural laws, the examination of physical systems allows us to determine the causes of their further time-evolution with arbitrary accuracy and thus allows us to calculate this further time-evolution in advance.

The difficulties with which the advocate of the causal law is faced through the discoveries of quantum mechanics thus do not stem from the principle of causality itself. Rather, they derive from the tacitly implied assumption that the body of physical knowledge describes the course of events in nature adequately and independently of a framework of observation. This statement is expressed in the assumption that every causal connection between events gives grounds for the predictive calculation of the effect from the cause, indeed that the causal connection is actually [even] identical with the possibility of this predictive calculation.

The theory of quantum mechanics forces us to resolve this mixture of different principles in the philosophy of nature, to drop the assumption of the absolute character of knowledge about nature, and to deal with the principle of causality independently of this assumption. Quantum mechanics has therefore not contradicted the law of causality at all, but has clarified it and has removed from it other principles which are not necessarily connected to it. φ

Endnotes

[1] Grete Hermann, "Die Naturphilosophischen Grundlagen der Quantenmechanik," *Die Naturwissenschaften* **42** (1935), p. 721.

[2] Grete Hermann, "Die Naturphilosophischen Grundlagen der Quanrtenmechanik," *Abhandlungen der Fries'schen Schule* 6,2 (1935), pp. 69-152, and "Die Naturphilosophischen Grundlagen der Quantenmechanik," *Die Naturwisseschaften* **42** (1935), pp. 718-721; Grete Hermann, E. May, and Th. Vogel, *Die Bedeutung der Modernen Physik für die Theorie der Erkenntnis* (Leipzig: S. Hirzel, 1937).

[3] Max Jammer, *The Philosophy of Quantum Mechanics* (New York: John Wiley & Sons, 1974), p. 209.

[4] Niels Bohr, *Atomic Theory and the Description of Nature* (Cambridge: Cambridge University Press, 1934).

[5] Niels Bohr, "Quantum Mechanics and Physical Reality," *Nature* **136** (1935), p. 65, and "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?" *Physical Review* **48** (1935), pp. 696-702.

[6] A. Einstein, B. Podolsky, and N. Rosen, "Can Quantum-Mechanical Description of Physical

Reality Be Considered Complete?" *Physical Review* 47 (1935), pp. 777-780.

[7] Hugh Everett III, " 'Relative State' Formulation of Quantum Mechanics," *Reviews of Modern Physics* 29 (1957), pp. 454-462; see also John A. Wheeler, "Assessment of Everett's 'Relative State' Formulation of Quantum Theory," *Reviews of Modern Physics* 29, 3 (1957), pp. 463-465.

[8] Byce S. DeWitt, "Quntum Mechanics and Reality," *Physics Today* 23, 9 (1970), pp. 155-165, and B. DeWitt and N. Graham, *The Many-Worlds Interpretation of Quantum Mechanics* (Princeton: Princeton University Press, 1973).

[9] David Z. Albert and Barry Loewer, "Interpreting the Many worlds Interpretation," *Synthese* 77 (1988), pp. 195-213.

[10] Michael Lockwood, "What Schrödinger Should Have Learned from His Cat," in Michael Bitbol and Oliver Darrigol (eds.), *Erwin Schrödinger: Philosophy and the Birth of Quantum Mechanics* (Cedex: Editions Frontièrs, 1992), pp. 363-384, and " 'Many Minds' Interpretation of Quantum Mechanics," *The British Journal for the Philosophy of Science* 47, 2 (1996), pp. 159-188.

[11] Simon Saunders, "What is the Problem of Measurement?" *The Harvard Review of Philosophy* 4, pp. 4-22, and "Relativism," in R. Clifton (ed.), *Perspectives on Quantum Reality* (Dordrecht: Kluwer, 1995).

[12] Saunders, "What is the Problem of Measurement?"

[13] Max Jammer, *The Philosophy of Quantum Mechanics*; M. Strauss, review of Grete Hermann, "Die Naturphilosophischen Grundlagen der Quantenmachanik," *The Journal of Unified Science (Erkenntnis)* 8, pp. 379-383; and Carl F. von Weizsäcker, "Zur Deutung der Quantenmechanik," *Zeitschrift für Physik* 118, 7-8, pp. 489-509.

[14] Hermann's term *Merkmal* is translated as "characteristic" in order to convey the vagueness of the original text. With respect to discussions that were to follow later in the history of interpreting quantum mechanics, however, a translation as "variable" would be more appropriate. [D.L.]

[15] The word *Beobachtung* is used to refer to a concrete particular here and is accordingly translated as "specific outcome of observation." [D.L.]

[16] Weizsäcker, "Ortsbestimmung eines Elektrons durch ein Mikroskop," *Zeitschrift für Physik* 70, 1/2 (1931), pp. 1143

[17] The term Beobachtungszusammenhang is translated as "framework of observation." [D.L.]

[18] In German: "an sich." [D.L.]

Initially published in German under the title "Die naturphilosophischen Grundlagen der Quantenmechanik" in Die Naturwissenschaften 42 (1935), pp. 71835).