A SPACE FOR THE QUANTUM WORLD

Ulrich Mohrhoff
Sri Aurobindo International Centre of Education
Pondicherry-605002 India
ujm@satyam.net.in

Abstract
Epistemic interpretations of quantum mechanics fail to address the puzzle posed by the occurrence of probabilities in a fundamental physical theory. This is a puzzle about the physical world, not a puzzle about our relation to the physical world. Its solution requires a new concept of physical space, presented in this article. An examination of how the mind and the brain construct the phenomenal world reveals the psychological and neurobiological reasons why we think about space in ways that are inadequate to the physical world. The resulting notion that space is an intrinsically partitioned expanse has up to now stood in the way of a consistent ontological interpretation.

1 INTRODUCTION

This article presents a new concept of physical space. Section 2 shows that the behavior of electrons in two-slit experiments is inconsistent with the notion that physical space is an intrinsically partitioned expanse. Section 3 explains why epistemic interpretations of quantum mechanics (QM) fail to address the puzzle posed by the occurrence of probabilities in a fundamental physical theory. This is a puzzle about the physical world, not a puzzle about our relation to the physical world. However, it is by examining how the mind and the brain construct the phenomenal world that we come to understand why we are prone to think about space in ways that are inadequate to the physical world. The concept of an intrinsically partitioned space stands in the way of a consistent ontological interpretation of QM. In epistemic interpretations the continuous extension and the spatial multiplicity of the world are phenomenologically grounded. In an ontological interpretation these features have to be understood as aspects of a strongly objective world. How this may be done is discussed in Sec. 4. Section 5 addresses the relation of the theory to the actual physical world. The key to this core interpretational issue is the objective indefiniteness that contributes to “fluff out” matter. It entails the extrinsic nature of the values of quantum-mechanical observables, which implies the contingent reality of spatial distinctions and the finite spatial differentiation of the physical world. Owing to the latter, the field-theoretic notion of an intrinsically and infinitely differentiated space is as inconsistent with QM as the notion of absolute simultaneity is with special relativity. Section 6 contains concluding remarks.
2 THE TWO-SLIT EXPERIMENT REVISITED

The strange behavior of electrons in two-slit experiments \[ \text{[1]} \] has led David Albert to the conclusion that “[e]lectrons seem to have modes of being, or modes of moving, available to them which are quite unlike what we know how to think about” \[ \text{[2]} \]. Albert arrives at this conclusion after considering what he claims to be “all of the logical possibilities that we have any notion whatever of how to entertain.” Each of the considered possibilities finds expression in a conjunction of two propositions, and thus is equivalent to the affirmation of two truth values, one for the proposition ”The electron went through the left slit” (symbolically, \(e \rightarrow L\), or \(L\) for short) and one for the proposition ”The electron went through the right slit” (\(e \rightarrow R\) or \(R\)):

\[
\begin{align*}
(1) & \quad e \rightarrow L \& e \not\rightarrow R, \\
(2) & \quad e \not\rightarrow L \& e \rightarrow R, \\
(3) & \quad e \not\rightarrow L \& e \not\rightarrow R, \\
(4) & \quad e \rightarrow L \& e \rightarrow R.
\end{align*}
\]

In the quantum domain, the sufficient and necessary condition for the existence of a truth value is a fact (an actual event or an actual state of affairs) from which a truth value can be inferred) \[ \text{[3, 4, 5, 6]} \]. If nothing indicates the truth value of \(L\) then \(L\) is neither true nor false but meaningless. In this case neither the property “through \(L\)” (represented by a subspace \(L\) of a Hilbert space \(\mathcal{H}\)) nor the property “through \(R\)” (represented by the orthocomplement of \(L\) in \(\mathcal{H}\)) can be attributed to the electron, nor does the corresponding binary observable (represented by the projector onto \(L\)) have a value. No property is a possessed property unless it is an indicated property. In other words, the values of quantum-mechanical observables are extrinsic (possessed because they are indicated) rather than intrinsic (indicated because they are possessed). They supervene on property-indicating facts.

If any of the above four conjunctions is true, no interference is observed. (The fourth conjunction is of course never true.) Albert’s conclusion that electrons can move in ways that we do not know how to think about is nevertheless unfounded, for his list is incomplete. There is another logical possibility:

\[
(5) \quad e \rightarrow L\&R.
\]

\(L\&R\) stands for the two slits considered as a whole. If the electron originates in front of the slit plate, and if \(L\) and \(R\) are the only openings in the slit plate, then (5) is true if and only if the electron is detected behind the slit plate. As the following section will show, the reason we tend to miss this possibility lies in our neurobiological make-up. This predisposes us to conceive of space as an intrinsically partitioned expanse—to believe that, no matter how we conceptually partition a spatial region, the individual partitions have an objective reality and are objectively distinct. This leads to the notion that space is intrinsically (“by itself”) partitioned into infinitesimal regions, and this notion, if it were correct, would justify the customary mathematical representation of space by the set \(\mathbb{R}^3\) of triplets of real numbers. But if every region of space were intrinsically and infinitely partitioned, proposition (5) would imply that either proposition (1) or proposition (2) is true. If \(L\) and \(R\) exist by themselves as distinct “parts of space” then
nothing goes through \(L&R\) without going through either \(L\) or \(R\) and without being divided into parts that go through different slits—the distinctness of the regions would imply the existence of distinct parts.

What the interference fringes are trying to tell us is that an electron is quite capable of going through \(L&R\) without going through either \(L\) or \(R\) and without being divided into parts. Proposition (5) does not imply that either proposition (1) or proposition (2) is true. The reason this is so is the extrinsic nature of possessed positions. Only indicated positions are possessed, and the only indicated positions are the finite sensitive regions of detectors. If the truth of proposition (5) is indicated then proposition (5) is true. If at the same time nothing indicates truth values for the propositions \(L\) and \(R\) then the electron’s position at the time of its passing the slit plate is \(L&R\), and it is not any smaller region inside \(L&R\). The individual regions \(L\) and \(R\) do not exist for the electron, and therefore they cannot “force the electron to chose between them.” A region \(V\) exists for an object \(O\) at a time \(t\) if and only if the proposition (\(P\)) “\(O\) is in \(V\) at \(t\)” has an (indicated) truth value. Space is not an intrinsically partitioned expanse. Partitions of space are contingent. A partition may be real for one object and not for another, at one time and not at another, depending on which propositions of the form \(P\) possess (indicated) truth values.

Most readers will have seen pictures of hydrogen orbitals. As is well known, the “electron cloud” represents a probability density \(|\psi_{n\ell m}(r, \theta, \phi)|^2\) rather than some “kind of bizarre real jelly” \([7]\). It is impossible to form a realistic image of an atom. The reason this is so is that nothing in the physical world corresponds to the intrinsically differentiated canvas of our mental images. We cannot help perceiving, and conceiving of, the space over which the electron cloud is extended as being divided into mutually disjoint regions. We may not actually imagine any particular partition of that space, but the idea that disjoint regions are individually existing and mutually distinct “parts of space” underlies our theoretical dealings with the world \([8, 9]\).

If \(|\psi_{n\ell m}(r, \theta, \phi)|^2\) is the right density for assigning probabilities to regions in the space of the hydrogen atom’s internal relative position \(R\), these regions exist solely in our imagination; they have no counterparts in the physical world. For this reason all we can say about \(R\) is counterfactual and probabilistic \([8, 9]\). Although we know very well that no physical detector (consisting necessarily of a large number of atoms) can monitor a region of space smaller than the size of an individual atom, we need to assume the existence of an array of detectors monitoring a set \(\{R_i\}\) of such regions, and we need to assume that exactly one detector clicks. If these conditions are fulfilled (which they never are) the integral of \(|\psi|^2\) over each region \(R_i\) gives the probability that the corresponding detector is the one that clicks. The detectors are needed to realize (make real) the mutually disjoint regions, if only counterfactually, for a region \(R_i\) is real if and only if a truth value exists for the proposition “The value of \(R\) is in \(R_i\)” (To be precise, the existence of a truth value is equivalent to the reality of \(R_i\) for \(R\). But if \(R_i\) is not real for the electron’s position relative to the proton, it is not likely to be real for the position of any object relative to the proton. And if a region is not real for any object, it is not real at all.)
As early as 1923, the year in which Louis de Broglie introduced electron waves and explained the quantization of orbital angular momentum postulated by Niels Bohr, Bohr wrote, “It is my personal opinion that these difficulties are of such a nature that they hardly allow us to hope that we shall be able, within the world of the atom, to carry through a description in space and time that corresponds to our ordinary sensory perceptions” [10]. Bohr did not say that a spatiotemporal description is impossible but only that such a description cannot be modeled after our ordinary sensory perceptions. This distinction seems to have been lost on his contemporaries, who instead of looking for an adequate spatiotemporal description discovered or re-invented Kant’s theory of science. Like Kant, they believed that space and time lie in the mind of the beholder. Science, accordingly, does not deal with the unperceived world; it deals with how the world appears to us, on the 3+1-dimensional canvas of mental space and time. Hence their insistence on the epistemic nature of QM [11, 12, 13, 14, 15].

As I see it, the key to a major puzzle posed by QM lies in the careful distinction between phenomenal space and physical space. Phenomenal space is the spatial aspect of the phenomenal world, of which we are directly aware. Physical space is the spatial aspect of the physical world (the world investigated by physical science) whose properties we need to discover or infer since we are not directly aware of them. The Kantian stance is appropriate for dealing with the phenomenal world. It is appropriate for classical physics because classical physics is consistent with the Kantian idea that the objective world is the totality of what appears (on the mental canvas of space and time). It is inappropriate for quantum physics because quantum physics is inconsistent with this idea, inasmuch as electrons never appear on the mental canvas.

Supporters of epistemic interpretations might counter that this is so because there are no electrons. According to Ole Ulfbeck and Aage Bohr [16], there are no electrons or neutrons; there are only electron clicks and neutron clicks. This point of view is founded on the claim that space and time have no mind-independent existence. If electrons do not appear (on our mental canvas), and if spatiotemporal concepts cannot be applied to what does not appear, then we cannot have knowledge of the properties of electrons. And if we cannot know their properties, we cannot know that they exist. Yet we do—how else could we talk about electron clicks and neutron clicks?—and for this reason we must reject the claim that spatiotemporal concepts are applicable only to what appears.

The antithetical claim has also been made that QM affords us a glimpse of the “veiled reality” [17] beyond the domain of experienced facts, and that this compels us to acknowledge something like the Kantian dichotomy between the world-as-we-know-it and the world-in-itself, and hence the merely intersubjective (weakly objective) reality of facts. However, as Kant’s idealistic successors were quick to point out, a reality that is by definition beyond our ken can play no role in our theoretical accounts of the world. Whereof we cannot say what it is thereof we must remain silent. Contrariwise, if we can meaningfully speak of what lies behind the “veil of appearances,” this forms part of the empirically known world. There is a dichotomy that is essential to QM, namely the dichotomy between a “classical domain” of property-indicating
facts and a “quantum domain” of properties indicated by facts, but this is a dichotomy within the empirically known world. It has nothing to do with the Kantian dichotomy \[3, 5\]. Only if it is decided beforehand that there are no spatiotemporal concepts appropriate to the quantum domain, does the quantum domain become unknowable like Kant’s world-in-itself.

Under the influence of quantum information theory something like the Kantian dichotomy is nonetheless gaining renewed popularity. (See, for instance, the correspondence of Christopher Fuchs with several distinguished physicists \[18\].) The idea seems to be that QM is necessarily about information because the information it is concerned with is about an unknowable reality. Quantum information, however, is not about anything unknowable. It is about possibilities and conditional probabilities: On condition that the values of a given set of observables \(Q_1, \ldots, Q_n\) are indicated at the given times \(t_1, \ldots, t_n\), QM assigns a joint probability to each set of possible values, on the basis of some chosen set of relevant facts \[4\]. It is therefore gratuitous to portray QM as being fundamentally about information. Since quantum information concerns probabilities, QM concerns probabilities rather than information.

The puzzle posed by the occurrence of probabilities in a fundamental physical theory is solved neither by invoking a reality beyond our ken nor by invoking the subjective aspect of our existence. It is a puzzle about the empirically known world, not a puzzle about our relation as conscious subjects either to the known world or to whatever lies beyond it \[3, 5, 19\]. However, while such words as “consciousness,” “experience,” or “information” have no legitimate place in interpretations of QM, an examination of the processes by which the mind and the brain co-produce the phenomenal world, can take us a long way toward understanding why we find it so hard to make sense of the physical world.

Consider the disparate ways in which we think about (i) a position or region of space and (ii) any other feature of the phenomenal world. We readily agree that the color of a ripe tomato or the shape of a sphere cannot exist by itself (not, at least, in the material world) without the existence of a material object of which it is the color or the shape. Yet we continually behave (mentally) as if a position or a region of space were something that exists by itself, whether or not there is a material object to which it can be attributed. What is ultimately responsible for the disparateness between our (conceptual) handling of positional information and our handling of other sensory data is the process by which the mind/brain system integrates into phenomenal objects such phenomenal variables as hue, lightness, shape, and motion. This integration is based on positional information. Phenomenal variables that occur in the same place are perceived as features of the same object, while phenomenal variables that occur in different places are perceived as features of different objects. Positional information thus plays a unique role in the process of feature integration. This uniqueness is reflected in the functional organization of the brain, where feature maps seem to be everywhere. (A feature map is a layer of the neocortex in which cells map a particular phenomenal variable in such a way that adjacent cells generally correspond to adjacent locations in the visual field. In the macaque monkey as many as 32 distinct visual feature maps have been identified.) While every phenomenal variable except location has at least one separate map, locations are present in all maps as the integrating factors \[19\].
While the features of each perceived object share the same phenomenal location, their neural correlates are scattered across a good many locations in the neocortex, and these different physical locations do not project (via neural pathways) on any single physical location: The brain lacks an “object map.” There is a master map where “it all comes together,” but this is not physical; it is the spatial aspect of our mental canvas—phenomenal space. This suggests to me that Kant was right in his insistence that space is primarily a subjective expanse, and that, epistemologically speaking, physical space is a projection or objectification of this subjective expanse. This, however, leaves open the question as to whether physical space is nothing but such a projection, or whether it is a mind-independent, strongly objective expanse, of which this subjective expanse is a more or less faithful reproduction. We ought not to anticipate the answer to this question by assuming beforehand that physical space is nothing but such a projection. Instead we should allow for the strong objectivity of physical space and deduce from this its actual properties. The question to be addressed, then, is this: Which of the properties of phenomenal space can be attributed to (a strongly objective) physical space, under which conditions, and to what extent? The answer to this question is not an all-or-nothing affair, as those implicitly assume who conclude that only the classical domain admits of a spatiotemporal description.

Recall the special role played by positional information in the construction (by the mind/brain system) of the phenomenal world. If we accord a mind-independent reality to the physical world, positional information cannot play an analogous role in the creation of the physical world. (If there are no neural correlates of the physical world, its creation cannot involve anything like neural feature maps.) The expanse of phenomenal space and a multiplicity of distinct phenomenal locations exist independently of what appears, for this expanse is a feature of our mental canvas, and the multiplicity of locations is rooted in our neuroanatomy—in the distinct physical locations of the neurons in each feature map. There is no corresponding foundation for the independent existence of physical space—indeed, that material objects—nor for the independent existence of a multiplicity of physical locations. The belief in the independent existence of an intrinsically differentiated physical space is therefore unwarranted. Not only is it unwarranted but it also prevents us from understanding QM. The fact that this belief is, as it were, “hard-wired,” explains why we find it so hard to beat sense into QM.

4 THE NATURE OF PHYSICAL SPACE

If the continuous extension of physical space and the spatial multiplicity of the physical world do not exist by courtesy of the mind/brain system, then how shall we conceive of them? The answer, in brief, is this: Physical space is the totality of spatial relations, or relative positions, that exist between material objects. The spatial multiplicity of the physical world, accordingly, consists in the (discrete) multiplicity of existing spatial relations. These relations have a qualitative as well as a quantitative aspect. The former consists in the quality of spatial extension; it constitutes the spatial character of each relation and does not connote any kind of multiplicity. The phenomenal world owes its spatial extension to the mental canvas on which it
appears. If we accord a mind-independent reality to the physical world, we cannot attribute its spatial extension to an independently existing expanse on which material things are “displayed.” Instead we must attribute it to each spatial relation. The spatial extension of the physical world is a quality that all spatial relations share.

It is worth noting, in passing, that the concept of an intrinsically partitioned physical space makes it impossible to understand the spatial unity of the physical world—except in weakly objective terms, as the projected unity of our mental canvas. Assume that physical space is a thing with parts and you are confronted with the task of explaining what holds together the parts of space. To my way of thinking, the proper way to cope with this task is not to take refuge in the secure haven of weak objectivity but to acknowledge the neural basis of the special treatment we accord to locations, to restrict this special treatment to the phenomenal world, and to treat physical locations in the same way as we treat the color of a ripe tomato or the shape of a sphere—as existing only if possessed. The task then reduces itself to explaining what holds together the parts of a material object. The purpose of this paragraph was to demonstrate that the concept of an intrinsically partitioned physical space is all that is needed to forestall any strongly objective conception of the physical world. This, however, should prompt us to look for a different concept of physical space, rather than to the rejection of strong objectivity.

There is mounting evidence from neuroscience that visual perception and visual imagination share the same processing mechanisms [21, 22]. It is therefore to be expected that the inherent graininess of phenomenal space also conditions our non-sensory visual images, including the images we form of hydrogen orbitals. Once we realize that the graininess originates in the neural constitution of our feature maps, we should find it easier to see that the parts of such an image do not represent material parts. Where there are material parts there are as many positions as there are material parts. Since the electron cloud represents a single (relative) position, such an image represents a single partless object. The parts of the image have a counterfactual reality, as was explained in Sec. 2. What about the extension of the electron cloud? Remarkably, this does represent an actual property of the hydrogen atom’s internal spatial relation, namely its quality of being spatial or extended. This shows that physical space, qua extension, can exist where spatial parts do not exist.

5 OBJECTIVE INDETERMINATENESS AND THE FACTUALITY PROBLEM

It is well known that the objective indefiniteness of relative positions is crucial for the existence of stable, extended material objects [23]. Together with the exclusion principle this is what “fluffs out” matter. Hence it would seem that finding a satisfactory formal expression of objective indefiniteness should be of paramount importance. The proper way of dealing with objectively indefinite values is to make counterfactual probability assignments [3, 4, 6]. If a quantity is said to have an “indefinite value,” what is really intended is that it does not actually have a value (inasmuch as the value is not measured) but that it would have a value if this were indicated, and that at least two possible values are associated with positive probabilities.

Since an observable may or may not have a value, we need a criterion for deciding when it
has a value, and this criterion consists in the existence of a value-indicating fact. The extrinsic nature of the values of quantum-mechanical observables (Sec. 2)—a rephrasing of the well-known necessity of describing quantum phenomena in terms of the experimental arrangements in which they are displayed—is therefore a straightforward consequence of their objective indefiniteness. Objective indefiniteness entails the possible lack of a value, which entails the need for a criterion, which consists in the existence of a value-indicating fact.

The problem of understanding QM is sometimes portrayed as the problem of explaining the emergence of facts (“classicality”) [25, 26, 27], but this cannot be taken literally. QM is concerned with correlations between property-indicating facts—diachronic correlations between results of measurements performed on the same system and synchronic correlations between results of measurements performed on entangled systems. QM presupposes facts, and therefore it cannot account for their existence. Nor can any other theory. Accounting for the existence of facts is the same as explaining why there is anything at all, rather than nothing—an impossible task.

In this regard quantum physics is no different from classical physics. Classical physics deals with nomologically possible worlds (worlds consistent with physical theory). It does not tell us which of all possible worlds corresponds to the actual world. Much the same is true of quantum physics. The main difference is that in classical physics the actual course of events is in principle fully determined by the actual initial conditions (or the actual initial and final conditions), while in quantum physics it also depends on unpredictable facts at later (or intermediate) times. There are just many more possible worlds, and there are many more extra-theoretical conditions to be satisfied by a possible world if it is to correspond to the actual world.

In order to solve the solid core of the measurement problem one must show that certain properties can be regarded as intrinsic—as factual per se—not only for all practical purposes but for all quantitative ones [3, 8]. The proof proceeds in three steps.

(1) Since no position is possessed unless it is indicated, and since nothing ever indicates an exact position, nothing ever has an exact position. Hence there exists some finite limit to the sharpness of the positions of material objects, and there exists some finite limit to the spatial resolution of actual detectors. Consequently there are objects that never evince their positional indefiniteness through unpredictable position-indicating facts—objects that evolve predictably in the sense that every time the position of such an object is indicated, its value is consistent with all predictions that can be made on the basis of (i) past indicated properties and (ii) classical laws of motion. This follows from the fact that evidence of departures from the pertinent classical laws requires detectors with sensitive regions that are small and localized enough to probe the range of values over which a position is distributed. If there is a finite limit to the sharpness of the positions of material objects, there are objects that have the sharpest positions in existence. The positions of such objects, which deserve to be called “macroscopic,” cannot but evolve predictably. We cannot be certain that a given object qualifies as macroscopic, inasmuch as not all relevant position-indicating facts are accessible to us, but we can be certain that macroscopic objects exist.

(2) If the positional indefiniteness of a macroscopic object never evinces itself through un-
predictable position-indicating facts—the occasional unpredictability of the position of a macroscopic pointer is an indication of the indefiniteness of a different observable—then what kind of reality does the positional indefiniteness of a macroscopic object possess? If we make the assumption that macroscopic objects follow definite trajectories, we will never see this assumption contradicted by facts. If instead we think of the position of a macroscopic object—a “macroscopic position” for short—as a “wave packet,” this is distributed over regions of space that are never objectively distinct. Such regions exist only in our imagination. They are the sensitive regions of detectors that do not exist in the physical world. They represent an unrealized degree of spatial differentiation. But if the position of an object is distributed over regions that do not exist, it is not actually distributed. The indefiniteness of a macroscopic position therefore has never more than a counterfactual reality.

(3) Now recall that the objective indefiniteness of the values of quantum-mechanical observables is the reason why they are extrinsic. Since the indefiniteness of a macroscopic position never evinces itself in the realm of facts, we can think of macroscopic positions as forming a self-contained system of positions that “dangle” causally from each other, rather than ontologically from position-indicating facts. We can ignore their extrinsic nature, consider them as intrinsic, and thus as factual per se. We can then attribute the possession of value, by a quantum-mechanical observable, to the value’s being indicated by at least one macroscopic position.

6 CONCLUSIONS

The transition from positions that supervene on facts to positions that form a self-contained causal nexus is quantitatively impeccable, inasmuch as the statistical correlations between indicated macroscopic positions are completely dispersion-free. Conceptually the transition is of the same nature as the transition from a purely correlative interpretation of the classical laws of motion (that is, from causality qua regularity) to an efficient interpretation that posits causal links responsible for the regularity. The latter transition is at bottom nothing but the projection, into the time-symmetric world of classical physics, of our own time-asymmetric agent causality [3, 6].

Classical physics is concerned with deterministic correlations that admit of a causal interpretation; quantum physics is concerned with probabilistic correlations that don’t, except in the classical domain. This is where the quest for meaning really begins, not where it ends. For the probabilistic correlations are trying to tell us something, something that concerns the nature of physical space.

While the whereabouts of macroscopic objects are abundantly indicated, they are never indicated with absolute precision. Hence even for macroscopic objects the world at any given time \( t \) is only finitely differentiated spacewise. That is, no finite region \( R \) is differentiated into infinitely many regions \( R_i \) such that truth values exist for all propositions of the form “\( O \) is inside \( R_i \) at the time \( t \),” where \( O \) is any macroscopic object. And this—the finite spatial differentiation of the physical world—is arguably the single most significant ontological implication of QM [3, 8]. The world is created top-down, by a finite process of differentiation, rather than built bottom-up,
on an infinitely differentiated space, out of locally instantiated physical properties. The field-theoretic notion of an intrinsically and infinitely differentiated space is therefore as inconsistent with QM as the notion of absolute simultaneity is with special relativity. Spatial distinctions are not intrinsic to space. They supervene on the facts. These constitute a domain whose indefiniteness exists only in relation to an unrealized degree of spatial differentiation (that is, only in relation to an imaginary backdrop that is more differentiated spacewise than is the physical world). Atoms exist beyond the realized degree of spatial differentiation, and this is what makes them so decidedly... alien.

To recapitulate, the indefiniteness of relative positions contributes to “fluff out” matter. The indefiniteness of the values of quantum-mechanical observables entails their extrinsic nature: No value is a possessed value unless it is an indicated value. This implies the contingent reality of spatial distinctions, and combined with a dynamical equation such as the Schrödinger equation, it implies the finite spatial differentiation of the physical world. This makes it possible to rigorously distinguish between the classical and the quantum domains, and to understand their mutual dependence. While macroscopic objects, like all composite objects, owe their finite volumes to the indefiniteness of their internal spatial relations and the exclusion principle, the properties of the quantum domain owe their existence to the classical domain: A position-indicating fact is necessary for the possession of a position, and a macroscopic detector is necessary for the existence of an attributable position—it realizes this position, counterfactually if not in actual fact.

The solution of a major puzzle posed by QM thus stands and falls with the finite spatial differentiation of the physical world. It cannot be found unless we relinquish our psychologically and neurobiologically sustained belief in an intrinsically (and therefore infinitely) differentiated space. It is this deep-seated but physically unwarranted belief that is responsible for our failure, so far, to find a sensible ontological interpretation of QM, and for our tendency to take refuge in epistemic interpretations.

References

[1] Feynman R P, Leighton R B and Sands M 1965 The Feynman Lectures in Physics Vol 3 (Reading, MA: Addison-Wesley) Sec 1–1
[2] Albert D Z 1992 Quantum Mechanics and Experience (Cambridge, MA: Harvard U P) p 11
[3] Mohrhoff U 2000a Am. J. Phys. 68 728–745
[4] Mohrhoff U 2001a Am. J. Phys. 69 forthcoming
[5] Mohrhoff U 2001b e-Print quant-ph/0102103
[6] Mohrhoff U 2001c e-Print quant-ph/0105097
[7] d’Espagnat B 1979 Sci. Am. 241 (5) 158–181
[8] Mohrhoff U 2000b e-Print quant-ph/0009001

10
[9] Mohrhoff U 2001d Proceedings of the 2nd International Conference on Integral Psychology (Pondicherry, 4–7 January 2001) forthcoming

[10] Honner J 1982 Stud. Hist. Phil. Sci. 13 1–29

[11] London F and Bauer E 1983 Quantum Theory and Measurement ed J A Wheeler and W H Zurek (Princeton, NJ: Princeton U P) pp 217–259

[12] von Neumann J 1955 Mathematical Foundations of Quantum Mechanics (Princeton, NJ: Princeton U P)

[13] Wigner E P 1961 The Scientist Speculates ed I J Good (London: Heinemann) pp 284–302

[14] Heisenberg W 1958 Daedalus 87 95–108

[15] Peierls R 1991 Physics World 4 (1) 19–20

[16] Ulfbeck O and Bohr A 2001 Found. Phys. 31 757–774

[17] d’Espagnat B 1995 Veiled Reality, an Analysis of Present-Day Quantum Mechanical Concepts (Reading, MA: Addison-Wesley)

[18] Fuchs C A 2001 e-Print quant-ph/0105038

[19] Clark A 2000 A Theory of Sentience (Oxford: Oxford U P)

[20] Mohrhoff U 2001e e-Print quant-ph/0102047

[21] Finke R A 1980 Psychol. Rev. 87 (2) 113–132

[22] Shepard R N and Cooper L A 1982 Mental Images And Their Transformations (Cambridge, MA: MIT Press)

[23] Lieb E H 1976 Rev. Mod. Phys. 48 (4) 553–569

[24] Bohr N 1963 Essays 1958–62 on Atomic Physics and Human Knowledge (New York: Wiley) p 3

[25] Joos E and Zeh H D 1985 Zeits. Phys. B – Condensed Matter 59 223–243

[26] Zurek W H 1991 Physics Today 44 36–44

[27] Zurek W H 1993 Prog. Theor. Phys. 89 281–312

Abstract (German translation): Epistemische Deutungen der Quantenmechanik lösen nicht das Rätsel, vor das uns das Vorkommen von Wahrscheinlichkeiten in einer grundlegenden physikalischen Theorie stellt. Dieses Rätsel betrifft nicht unsere Beziehung zur physischen Welt, sondern die physische Welt selbst. Seine Lösung erfordert einen neuen Raumbegriff, der in diesem Artikel vorgestellt wird. Eine Untersuchung der geistigen und neurobiologischen Wurzeln der Erscheinungswelt klärt, warum unser Denken über den Raum der physischen Welt nicht gerecht wird. Die diesem Denken zugrunde liegende Idee, dass der Raum innerlich zerteilt ist, stand einer konsequenten ontologischen Deutung bisher im Wege.