The high-energy interpretation of quantum mechanics

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Abstract

We address the issue of the interpretation of quantum mechanics by asking why the issue never arises in the description of high-energy interactions. We argue that several tenets of quantum mechanics, specifically the collapse of the wave function, follow directly once one accepts the essential randomness of fundamental interaction events. We then show that scale separation of fundamental interactions ensures that the decoherent measurement can be unambiguously separated from the random quantum events. Finally, we argue that the fundamental symmetries of space and time guarantee the existence of a unique preferred basis. We argue that this set of ideas might lead to an interpretation of quantum mechanics, or rather, show in which sense an "interpretation" is (or is not) necessary.

1. The quantum world and its "paradoxes"

It is a commonplace statement that the laws of quantum mechanics are strange and to some extent paradoxical: a statement which is reflected not only in the titles of popular science books (see e.g. [1, 2]) but also in chapter headings of textbooks (e.g. "Abandoning realism" in Chapter 3.7 of [3]) or even titles of papers (see e.g. [4]). Of course, in popular science this situation is by no means unique: relativity, say, (even special relativity) is also often described as puzzling and paradoxical. However, as any physicist (in fact, any decent physics undergraduate) knows, special relativity expresses the kinematic properties of physical laws in a way which is neither more complicated nor less intuitive than Galilean relativity. Indeed, both special relativity and Galilean relativity are easily understood by reflecting on simple thought experiments. The only reason why Einsteinian relativity is somewhat less intuitive than its Galilean counterpart is that the thought experiments on which it is based can be easily referred to everyday experience —such as the original discussion by Galileo of moving ships [5]— while the thought experiments of relativity require objects that move close to the speed of light. Indeed, the idea that relativity would be part of the common-sense everyday

experience of living beings moving close to the speed of light has been exploited in the classic popular presentation by G. Gamow [6].

However, quantum mechanics is different. On the one hand, there is overwhelming evidence that quantum mechanics provides the underlying grammar for all fundamental physical laws, with no evidence of deviations from it, either at a fundamental level (i.e., when shorter distances are tested) or at a macroscopic level (i.e., when the quantum behavior of systems consisting of an ever larger number of degrees of freedom is tested). On the other hand, the standard formulation of quantum mechanics requires introducing, in the process of measurement, the interaction of the quantum system with a classical measuring apparatus. Most physicist would argue that this is surely an approximation, in that quantum mechanics applies at all scales, and there is no such thing as a classical realm. Certainly, as mentioned, there is not a shred of experimental evidence of macroscopic deviations from quantum behavior which would allow for a separation between quantum and classical worlds.

But then, if the measurement process as usually formulated is an approximation, it is an approximation to what? There seems to be no full consensus on the exact nature of the quantum to classical transition and therefore, while most would agree that measurement is driven by decoherence caused by entanglement with a macroscopic measuring apparatus (see e.g. Sect. 20.3 of [7] for a standard textbook presentation), there seems to remain some fundamental underlying lack of understanding. The laws of quantum mechanics are fundamentally strange, because an interpretation is required in order to explain what they really mean. Indeed, there exist numerous "interpretations" of quantum mechanics (see e.g. 3.7 of [3]): effectively, different interpretations of quantum mechanics amount to an explanation of what the standard set of quantum-mechanical rules are supposed to approximate — with the Copenhagen interpretation consisting of acceptance of the rules at face value.

Yet, in all contexts in which quantum mechanics is being used, the way it should be used is absolutely clear. To the best of our knowledge, there is not a single case in which the prediction of quantum mechanics are ambiguous, even less a case in which an interpretation is required in order to resolve the ambiguity. It is thus natural to turn to the everyday use of quantum mechanics as a way to resolve its strangeness: after all, if we know what the theory means in all possible contexts, what more is there to say?

In the sequel, we will briefly discuss some aspects of quantum mechanics in light of their use in the context of high-energy physics, i.e. the physics of interactions at the shortest distance scales which are probed in experiments such as those which are being performed at the Large Hadron Collider of CERN [8]. We will show how many of these aspects are taken for granted when using theoretical calculations to obtain predictions which may be tested against experiment, and how this makes many aspects of quantum mechanics look rather less paradoxical than they might appear at first. We will suggest that this set of

ideas might perhaps lead to a full-fledged "interpretation" of quantum mechanics, which we dub the "High-Energy Interpretation of Quantum Mechanics": though, in actual fact, what we are really talking about is, somewhat more modestly, the way of looking at quantum mechanics which is suggested by its use in the context of high-energy physics. It will be left to the reader to decide whether at present, or perhaps at some later stage, this deserves the somewhat exalted name of "interpretation". It should be clear from the onset, however, that we will not be presenting any new results, and merely collecting some ideas that upon reflection are obvious: certainly obvious to any high-energy physicist.

2. Randomness and collapse of the wave function

The basic quantities which are computed and compared to experimental results in high-energy physics are scattering cross-sections (and decay rates). A fundamental feature of this comparison of theory with data is that it involves accepting the fundamentally random nature of physical events.

Take the simplest scattering process, elastic electron-positron scattering (Bhabha scattering), as it was for instance observed at the LEP collider of CERN [9] (where, among other things, it was used to measure the luminosity of the machine). Quantum electrodynamics, i.e. quantum mechanics applied to the electromagnetic interaction, and its extension to also include the weak interaction (the electroweak standard model) provide us with a prediction —a very precise prediction indeed— for the angular distribution of the outgoing electron-positron pair. In each individual scattering event, the outgoing particles exit in one particular direction. Their energy is fixed by conservation of the incoming particle energy, and their momenta must be equal and opposite by conservation of the total momentum. But the exit angle is not fixed. Quantum mechanics tells us that if the experiment is repeated many times, we can predict on average the angular distribution of the outgoing particles (to astounding accuracy), but not their exit angle in each individual instance. This angular distribution is computed as a function of the initial conditions, i.e. the momenta of the pair of incoming, colliding particles, and it is fully determined by them. Unlike in a classical scattering event, where uncertainty in the final state is only related to imperfect knowledge of the initial conditions, or, possibly, of the structure of colliding objects, this randomness has to do with the fundamental nature of reality. Even when observing the scattering of electrons (which are pointlike object with no structure) with fully determined initial momenta the exit direction cannot be predicted.

Once the particles do exit in one specific direction, we can take this as initial condition for a subsequent quantum mechanical event. For example, if the colliding particles were muons, instead of electrons (muon colliders have not been built yet, but are actively studied [10]) one might compute the chance that either of the two outgoing muons will then decay. Quantum mechanics then provides us with a determination of the probability that each muon may decay at any given time, and the angular distribution and energy of its decays products, as a

function of the initial muon momentum, and indeed such bread-and-butter calculations are routinely performed and used for example in the calibration of particle detectors.

Summarizing, individual high-energy interactions are random: what the laws of physics allow us to do is predict their behavior on average as a function of the initial conditions. The outcome (the final state of the interaction) can then be taken as a new initial condition for a subsequent calculation and prediction.

It should be clear that this simple situation is at the root of the so-called "collapse of the wave function". The wave function of the initial colliding particle pair is the initial condition: it provides us with the information on the state of the system.[1] Its knowledge only allows us to compute probabilities of outcomes, which are then observables. After the observation of an actual outcome, our information on the state of the system (which we may use as initial condition for a subsequent measurement) changes. But the information on the state of the system is encoded in the wave function, so the wave function must change when we observe an actual individual outcome. After the measurement, the wave function no longer gives us a probability: rather, it is in the state which corresponds to the observed outcome. We can then use this new wave function to compute probabilities of subsequent events.

It is thus recognized that if one accepts that individual events are fundamentally random, and their outcome can only be predicted on average, then it follows that the information on the state of the system changes discontinuously when an individual outcome is observed. Often in popular presentations this discontinuous change is described with statements such as "the observer perturbs the system". But this seems at best to miss the main point, and in the worse case rather misleading: when observing the outcome of an experiment ("performing a measurement") what does change, and discontinuously at that, is the observer's information on the state of the system.[2]

Acceptance of this simple fact —the fundamental randomness of individual events— helps in dispelling some of the mystery that sometimes appears to shroud many of the basic tenets of quantum mechanics. For example, the postulate of quantum mechanics states that an observable is associated to a Hermitean operator follows from the fact that the outcome of an experiment (i.e. the outcome of a measurement) is not unique. In our example, we assign a different state of the system $|i\rangle$ to each direction of the electron-positron pair. It is perhaps worth noticing that in any realistic situation the set of such states is always discrete. For example, a detector can measure the particle momenta only with a certain resolution, so the outgoing angle can only take a discrete set of values. Indeed, experimental results for angular distributions are presented in the form of histograms, in which the value of the momentum is

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[1]This information might actually be incomplete; use of a density matrix formalism allows a treatment of this more general case, but this is besides our point now.

[2]The somewhat quaint description of the measurement as a perturbation of the system can be traced to Heisenberg (see e.g. [11]).

provided in discrete bins.[3] So, after detecting the outgoing pair, the system is found in one of the states $|i\rangle$, which are each characterized by a different value of some observable, say an angle θ_i. The system is to be found with probability p_i in state $|i\rangle$.

The observed mean value of the angle is

$$\langle \hat{\theta} \rangle = \sum_i \theta_i p_i \tag{4.1}$$

We can rewrite this by defining an operator $\hat{\theta}$, as the matrix in the space spanned by states $|i\rangle$ which has values θ_i on the diagonal. This definition is natural in that the mean value of $\hat{\theta}$ is then found by tracing the product of this matrix with a density matrix ρ, in turn defined as the matrix which has the probabilities p_i of outcomes in the diagonal:

$$\langle \hat{\theta} \rangle = \mathrm{Tr}\hat{\theta}\rho. \tag{4.2}$$

The Hermitean nature of $\hat{\theta}$ (and ρ) then simply follows from the assumptions that the outcomes of the experiment are distinct (i.e. orthogonal), and that they are each characterized by a real number (the eigenvalues — not necessarily distinct!). It should be clear that in this line of argument only the simple principle of the statistical nature of experimental results has been used: the observable is an operator because after the measurement there is a distribution of distinct outcomes. This does still not fully derive the Born rule - the fact that the state of the system can be viewed as the superposition

$$|\psi\rangle = \sum_i c_i |i\rangle \tag{4.3}$$

such that $p_i = |c_i|^2$, though it is clear that Eq. (4.2) goes a long way in this direction.

We have thus understood the meaning of two basic axioms of quantum mechanics —the measurement and collapse of the wave function, and observables as Hermitean operators— and we have a strong hint on the nature of another one — the Born rule. Many consequences which are derived from them also appear perhaps less surprising and unusual, once seen as statements about fundamentally random physical events of which only the probability distribution can be predicted.

While many examples could be given, we consider here only one of the simplest if not the simplest, namely the uncertainty principle. If fundamental physical events are random, then their distribution is characterized not only by a mean value Eq. (4.1), but also by a standard

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[3]Clearly, this is also due to the fact that the number of individual events on which each experimental measurement is based is finite, but even in the limit of a very large number of events the spacing of measured momentum values can never be finer than the detector resolution.

deviation

$$\Delta^2 \hat{\theta} \equiv \sigma_\theta^2 = \langle \hat{\theta}^2 \rangle - \langle \hat{\theta} \rangle^2. \tag{4.4}$$

The uncertainty principle is then merely a statement about the mutual size of standard deviations of measurements of distinct observables for a system in a given state. Needless to say, the standard deviation is a property of the set of repetitions of the experiment, not of any individual instance. It may be surprising that some pairs of observables cannot be simultaneously sharp (because the product of their standard deviations is bounded from below) in some states, or perhaps even in all states. But it is clear that, again, this is not a statement about what the observer does to the system, rather it is a statement about an ensemble of repetitions of an experiment performed on many identically prepared system.[4]

3. Superposition and scale separation

The Bhabha scattering process discussed in Sect. 2. can proceed through several "channels", as the jargon goes. Namely, the incoming pair can produce either a photon or a Z, each of which can then go into the given final state.[5] In fact, at LEP1 (the first phase of running of LEP) the energy of the collision was tuned in such a way that real Zs were being produced — the energy of the collision was tuned to be equal to the mass of the particle, so one could actually view the Z channel as consisting of production of a Z particle followed by its subsequent decay. Yet, of course, the probability for producing the final electron-positron pair is not obtained by combining the probabilities of going through the Z and photon final states, rather, by combining the amplitudes.

It might be interesting to ask to which extent this postulate of quantum mechanics —that amplitudes, not probabilities are combined— could be derived starting with the argument of the previous section, based on fundamental underlying randomness, and imposing further consistency conditions.[6] Here however we will not pursue this line of argument, and instead ask whether this is problematic, and if not, why not.

The fact that events are random does not seem paradoxical or contradictory per se: one can simply conceive factual reality as a sequence of events of which only the probability is determined a priori. The future can be viewed as an infinitely branching tree, of which only one branch is realized. The repeatability of situations (initial conditions) makes predictivity possible, on a statistical if not on a deterministic basis.

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[4]This amounts to realizing that the uncertainty principle relates the uncertainty of pairs of observables *before* a measurement. The value of the uncertainty of an observable *after* the measurement of another observable which does not commute with it is a separate issue, and has in fact been studied recently [12]

[5]More intermediate states are possible in higher orders of perturbation theory.

[6]On top of these, the only remaining postulate of quantum mechanics is time evolution, i.e. the Schrödinger equation. This can be derived from the requirement that quantum mechanics preserves the canonical structure, i.e. that time translations are generated by the Hamiltonian, or, equivalently, that time translation invariance implies energy conservation.

However, the fact that amplitudes, rather than probabilities, should be combined, does seem to entail some complications, in that it implies that the branching tree cannot be defined with excessive resolution. For example, in the classic double slit experiment we cannot view the trajectory that leads to the detection of a particle in a specific point of the screen as a sequence of random events, the first of which leads the particle randomly (though with fixed probability) from the source to one of the slits, times a second event which leads it randomly (though with fixed probability) from the slit to the screen: this would correspond to composing probabilities, and it would not lead to the observed interference pattern.

Nevertheless, it is to some extent possible to decompose the evolution of a quantum system. Namely, one may define a "consistent history" [13], i.e. a set of branchings such that indeed the history of a given quantum system can be viewed as a sequence of intermediate random events. Of course, this is possible to the extent that the different branchings do not interfere with each other. In other words, provided the branching tree is sufficiently "coarse grained" one can view the evolution of the system as a sequence of random events, but if it is excessively fine grained, this becomes impossible because then alternative histories interfere, so there is no sense in which only one of them could have been actually realized: if the paths through the two slits interfere, then there is no sense in which the particle could have actually passed through either.[7]

Be that as it may, one might wonder why in practice in the application to any high-energy physics experiment these issues clearly never arise. One never has to ask which is the random event: in the example above, it is the elementary electron-positron scattering. One never has to ask what is the initial condition: it is provided by the wave function of the initial electron-positron pairs, which at a collider are momentum eigenstates. And there is likewise no doubt about what is the measurement: it is the observation of the outgoing electron and positron in the detector, which, because the detector is designed to determine the values of the energy and momentum of the outgoing particles, leads to an initial condition for subsequent events —a final state wave function— which also corresponds to momentum eigenstates.[8]

The answer to the question of why this is so is clear upon a minute's reflection: scale separation is the reason why one never has to deal with the issue of what is the random event and what is the measurement, or, in the language of the consistent histories, the issue of what are the projection operators and what is the amount of coarse-graining required to consistently define the history. In our example, the scale which defines the elementary interaction is that of the electroweak interaction: in a scattering event at LEP it would be of the order

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[7]However, one may define a generalized probability over the quantum evolution of a system which satisfies all criteria of standard probability, but not positivity. Whenever the set of probabilities of all individual branches do satisfy positivity, then the histories are sufficiently coarse grained, i.e., the question of which sequence of random event has led from the initial to the final condition does have a meaning — it is a "settlable bet" [14].

[8]The measurement itself can then be unproblematically described in the language of decoherence e.g. summarized, as already mentioned, in Sect. 20.3 of [7].

of 100 GeV, corresponding[9] to a length scale of about 10^{16} cm^{-1}. The initial states are not really momentum eigenstates: they are wave packets, and in fact the standard expression for the scattering cross-section involves a factor to account for the flux of incoming particle derived (as explained in any good textbook [15]) assuming the incoming particles to be given by wave packets whose momentum uncertainty is small in comparison to the momentum scale of the interaction, so their wave function is spread over much larger distances (for example, 100 MeV, corresponding to 10^{13} cm^{-1}): if the momentum scale of Δp is by a factor of say 1000 smaller, the associate Δx is by a factor 1000 larger.

The incoming particles are typically prepared in a bunch, spread over much larger distance scales, and with approximately constant particle density (a proton bunch at the LHC has a size of about $10\mu m = 10^{-3}$ cm). Likewise, the final state is observed at distances which are macroscopically large in comparison to the distance of the interaction: even the closest detector, such as the pixel detectors of LHC experiments, observe particles at distances of about $10\mu m = 10^{-3}$ cm from the interaction point. They reveal states whose momentum uncertainty is again much smaller than that of the interaction which is being studied, and which are seen by reconstructing tracks whose width (i.e., position uncertainty) is typical of distance scales of the solid-state electronic devices which are used to detect them, i.e. again a few μm at most.

Therefore, the problem does not arise because the characteristic distance scale of the incoming and outgoing states, on one side, and that of the interaction, on the other side, are separated by many orders of magnitude. This, in turns, reflects the setup of the devices which are used to prepare the incoming particles and to detect the outgoing ones. The amount of coarse-graining is thus fixed by the natural scales of the problem.

Whereas we have illustrated this situation in a particular example, it is in fact generic, and it provides the language in which high-energy physics experiments are described and designed, both from a technical, and a more informal point of view. Indeed, the fact that "in" and "out" states are prepared at scales which are so well separated from the interaction that they can be described by a free theory is part of the basic underlying formalism of quantum field theory [16]. That "in" states are momentum eigenstates from the point of view of the quantum-mechanical computation, but really wave packets from the point of view of the determination of a macroscopic cross-section is part of the way the cross-section is computed: as already mentioned, the flux factor, which is an integral part of the cross-section, is obtained using this assumption in a crucial way. That the "out" states are momentum eigenstates, measured by reconstruction of a "particle trajectory", is an accepted fact which underlies experimental design. Here "particle trajectory" is put in quotes because, of course, a quantum-mechanical momentum eigenstate has completely uncertain position and thus no trajectory. But in realistic experiments, as in the above example, one deals with particles

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[9]With $\hbar c = 1$, so 197 MeV$\approx 10^{13}$ cm^{-1} (natural units).

whose momenta are measured with an uncertainty of, say tens or hundreds of MeV, by measuring tracks whose width (even less whose lengths) never go below the μm scale, at least six or seven orders of magnitude below the limit set by the uncertainty principle: these wave-packets may be treated as momentum eigenstates for all practical purposes.

Hence, the separation of scales between preparation, interaction, and detection, guarantees first, that one may view the fundamental interactions of high-energy physics as essentially random events which are preceded and followed by well-define measurement processes with no ambiguity, and second, that this measurement process, even though fully quantum-mechanical in nature (because one measures the properties of a single particle, such as a single electron, which is surely a quantum-mechanical system) can be described in semi-classical terms, as when stating that a particle's momentum is determined by looking at the curvature of its trajectory when it is subject to a magnetic field.

Whereas we have only given the simplest example, it turns out that this separation is at work even when this semi-classical language is used to describe purely quantum-mechanical phenomena. For example, neutrino oscillations (see e.g. [17] for a textbook presentation) involve the time-evolution of states which are the superposition of two different energy eigenstates, so that the superposition coefficients depend on time. The standard language used to describe them treats the eigenstates as particles that propagate in space as a function of time, though, again, strictly speaking an energy-momentum eigenstate would have fully uncertain position: so, in principle, only a description in terms of wave packets would be correct [18], but it turns out that in practice the standard "semiclassical" description is fully adequate [19] because the scale of the interaction used to prepare the incoming neutrino beam and to reveal the outgoing neutrino states is characterized by enormously greater length scales in comparison to that which drives the neutrino oscillation itself.

In summary, the language of "particle flux", "interaction" and "particle detection" separates the act of measurement with that of quantum-mechanical evolution, without having to loose the quantum-mechanical nature of the incoming and outgoing states, and even without fully erasing the quantum-mechanical nature of the act of measurement itself.

4. Multiple descriptions and preferred bases

We have seen that our basic example of a simple quantum scattering process can be viewed as a random event which connects an initial state in which the two incoming particles are in momentum eigenstates to a final state in which a measurement also reveals them in momentum eigenstates. It is clear, however, that the choice of basis states for the description of the fundamental random event is not unique: we could have made, for instance, the choice of describing the process in terms of position eigenstates.

There are well known examples in which the same quantum evolution process may be viewed in different but completely equivalent bases (for instance, for spin systems in which different spin components are diagonalized [13]). In each basis it is possible to provide a sufficiently coarse-grained description, so that the full evolution from initial to final state is consistently expressed as a sequence of random events — so that at each intermediate state it is possible to say which of the alternative histories is actually being realized by the system. Equivalently, it is possible a posteriori to settle the bet of which of the paths of the branching history tree the system is following in a particular sequence of events. Yet, the descriptions might be given in terms of bases of eigenstates of incompatible (i.e. non-commuting) operators, in such a way that different inequivalent descriptions of the same history are possible. This means that it is not possible to state that at some intermediate time the system was objectively in one state, because in, say, a pair of different, equivalent descriptions (based on an arbitrary basis choice) the system was respectively in one or another state which belong to incompatible bases. Therefore, one cannot say that, in that history, the random event of the state being in one particular eigenstate of either of these two bases "actually happened". But the requirement that "something happens" has been advocated [20], quite reasonably, as a requirement for a satisfactory formulation of quantum mechanics.

Once again, one may wonder why this issue never arises in high-energy physics settings. In our example, it is clear that the incoming and outgoing particles are in momentum eigenstates (well, approximate eigenstates, really, as discussed in the previous section), and that the transitions induced by the fundamental interaction, which the Feynman diagram formalism treats using standard time-dependent perturbation series and the Dyson series, are transitions between different momentum eigenstates induced by multiple insertions of the Hamiltonian.

Specifically, one might wonder whether an equivalent description in terms of, say, position eigenstates would be possible — perhaps with a slightly different experimental setup such that position, instead of momentum eigenstates are preferentially detected. If this were the case, one could choose to view the very same elementary interaction as actually leading to a transition between position eigenstates, and our naive conviction that in each scattering event a random transition between different momentum eigenstates has happened would be actually fictitious.

A minutes' reflection reveals that this is not the case. The reason has to do with the fundamental structure of quantum field theory, i.e. the quantum mechanics of space-time systems with infinite degrees of freedom. Namely, in the nonrelativistic quantum mechanics of one or many particles in space, the coordinate and momentum representations of the wave function are entirely equivalent: we can expand the wave function over a set of position eigenstates, or momentum eigenstates, and none is preferred over the other. Not so in quantum field theory. Indeed, in (free) field theory the Hamiltonian is diagonalized in the basis of momentum eigenstates: the Hamiltonian in position space describes a system of coupled harmonic

oscillators, each localized at a point in space, which are diagonalized by normal coordinates which coincide with momentum eigenstates. This is a consequence of the structure of the free-field kinetic term as the operator with the smallest number of spacetime derivatives, i.e., ultimately, it follows from the fact that elementary excitations of space and time can always be described at the shortest distances as small oscillations about an equilibrium state.

If one also considers the behavior of the fundamental excitations upon spacetime rotations, momentum degrees of freedom are supplemented by spin. In the high-energy limit, all excitations are effectively massless, and massless excitations are helicity eigenstates, i.e. they have spin parallel to the momentum axis. Hence, even in the case of spin degrees of freedom, there is a preferred basis: than in which spin is quantized along the direction of momentum. This is the only basis which admits a well-defined short-distance limit. But the existence of a short-distance limit is a basic requirement for any fundamental theory, i.e. one that is meaningful at all length scales.[10]

We must conclude that the basis of momentum eigenstates, supplemented by spin quantized in the direction of momentum, is selected by the fundamental interaction, for reasons which have to do with the structure of space and time. This can also be seen when asking what we mean by "elementary particle": namely, an eigenstate of mass and spin. This follows from the requirement that elementary particles be eigenstates of the Casimir invariants of the Poincaré group, which is the invariance group of spacetime.

It is interesting to observe that scale separation, as discussed in the previous section, guarantees that the relevant momentum eigenstates are always uniquely defined. For example, neutral kaons are produced as mass eigenstates. However, the mass eigenstates are not also eigenstates of the Hamiltonian which leads to their decay. As a consequence of this, neutral kaons oscillate due to quantum evolution, but the fact that the scale of their masses (hundreds of MeV) is distinct from the scale of the weak interactions (hundreds of GeV) guarantees that the kaon decay, which selects the weak eigenstates, is well separated from the propagation of the mass eigenstates. Indeed, the two different weak eigenstates are distinguished by the length of their trajectories ("long" and "short") — here one sees again the semiclassical picture at work (as in the case of neutrino oscillations) whereby one may talk of trajectory of a quantum state, meaning that one is talking about a wave packet, which can be viewed as a momentum eigenstate from the point of view of the fundamental underlying quantum interaction, because the momentum uncertainty is much smaller than the position uncertainty.

Admittedly, the argument given here is by no means a general proof. However, to the best of

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[10]Clearly, the same line of argument can be pursued when dealing with internal symmetries, where the scale separation of different interactions allows one to measure the degrees of freedom of one interaction —such as, say, the isospin of strongly-interacting neutrons— using decay through another interaction — such as neutron β decay mediated by the weak interaction. See below for another example in neutral kaon decay.

our knowledge, the textbook situation [13] in which multiple incompatible descriptions of the same quantum history are possible has never arisen in the context of any realistic high-energy physics experiment. Our line of argument suggests that this is not accidental, but rather, that it follows from deep properties of quantum field theory which in turn reflect the way spacetime symmetries are realized in the theories of fundamental interactions.

5. An interpretation of quantum mechanics?

In this essay, we have addressed the problem of the interpretation of quantum mechanics by asking why an interpretation does not seem to be necessary at all when applying quantum mechanics to high-energy physics, i.e., when using quantum mechanics to study the theory of "fundamental" interactions, namely, those which describe physics at the shortest distances. We have argued that several tenets ("postulates") of quantum mechanics follow directly from recognizing the fundamental randomness of basic ("interaction") events. These include the collapse of the wave function and the identification of observables with Hermitean operators. Furthermore, we have argued that the description of quantum mechanical evolution in terms of random events which connect distinguishable states ("consistent histories") is always possible in this context because of the natural scale separation of fundamental interaction events which in turn follows from the structure of the interaction itself. Finally, we have argued that this consistent history description is unique (so that one may view the events which form it as having "actually happened") because the basic symmetries of spacetime select momentum (over position) and helicity (over other components of spin) as preferred bases.

The fact that these considerations apply to the theory of fundamental interactions suggests that their interest is more than anecdotal. Indeed, standard Wilsonian renormalization group argument (see Ref. [16]) suggests that the physics at the shortest distance scales is "fundamental" in the sense that lower-energy physics can be derived from it in the form of an effective theory, by integrating out degrees of freedom. If one can put on a firm footing an argument which shows that no interpretative issues arise when applying quantum mechanics at these scales, then this suggests that such interpretative issues might be an artifact of the low-energy effective description.

Of course, this would require first, turning the simple arguments presented here into more formal proofs, and second, filling in the numerous gaps (e.g. by showing how also the Born rule is necessary, and so forth). We call the completion of this program the "High-Energy Interpretation of Quantum Mechanics" — effectively, a way of showing that no interpretation of quantum mechanics is really needed.

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