QUANTUM MECHANICS WITHOUT MIRACLES

I. QUANTUM DISTRIBUTIONS, PARADOXES, AND WAVE-PARTICLE DUALITY

Current version: April 2022

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Arguing that the orthodox quantum mechanics (QM) in its statistical interpretation is sufficient to plainly explain long distance correlations between entangled particles without resorting to exotic hypotheses such as nonlocality / "spooky actions" and the like. The critical element here is the recognition of a difference between languages and notions of classical mechanics (CM) and QM: QM is a statistical phenomenology, not describing individual particles, but rather their large congregations / collectives – quantum ensembles. In doing so, QM operates with complex valued distribution functions – wave functions (WFs) – built in a full compliance with conservation laws as a superposition of partial components explicitly preserving pertinent dynamics variables. Further, in contrast to a popular misconception an entanglement is to no extent an exotic phenomenon: on the contrary, it has been routinely emerging in QM's almost centennial treatment of molecular, atomic, nuclear and elementary particle physics and never caused the need for a "supernatural" nonlocality. Relatedly, the very same CM-QM language incompatibility results in seemingly paradoxical features of a two-slit diffraction and similar experiments. Further, we discuss in some detail the distributional interpretation of wave functions and their superposition as well as "virtual" vs "real" notions in QM along with their manifestation in measuring processes. Finally, we address the genesis and evolution of wave-particle duality (WPD) and potential perspectives into its future developments.

Key words: classical mechanics, quantum mechanics, Schrödinger equation, wave function, principle of superposition, probability amplitude, distribution function, wave-particle duality, quantum nonlocality.

Introduction.

The fast-approaching 100s anniversary of quantum mechanics (QM) is marked with an astonishing record of stellar accomplishments and beginning the era of quantum computers, and yet, with no consensus on QM foundations and interpretations. Quite conspicuous in this context is a persistence of number of paradoxes, most vexing being the nonlocal interpretation and "spooky actions at the distance".

The key root of the "spooky" problem is ignoring a simple fact that QM speaks the language fundamentally different from classical mechanics (CM). While CM describes the nature by the Laplace-Cauchi determinism (i.e., Cauchi problem for each particle/trajectory), QM, broadly speaking, is a "statistical phenomenology", which doesn't describe individual events, but only their statistics. Further, in classical physics all processes proceed with full certainty (at least, in principle) via one channel (Cauchi trajectory) of events dictated by conservation restrictions. In QM this unique mode of

development splits into infinitely many potential channels / potentialities, yet each complying with conservation laws. It is attempting to explain that conservation in each quantum channel by classical logic that creates a “nonlocality” problem.
What’s more, differing QM outcomes and associated with them ”virtual” processes, not fitting the classical framework, have unequivocal experimental manifestations, e.g., tunnel effect / alpha decay, exchange energy, Bose- and Fermi-statistics, direct nuclear reactions, long-distance correlations of non-interacting particles, etc.

This note attempts to heuristically outline and possibly demystify the most glaring “nonlocality” paradox and related misconceptions. In the interest of readability, we adopt a most elementary language to embrace readers of even a cursory familiarity with QM, and also, do not include a potentially formidable list of references, except for a few classic sources.

Accordingly, in Sec. 1 we begin with a brief history and argument of “nonlocality” and “spooky action”. Then Sec. 2 explains why wave functions are not material waves, but, in fact, distribution functions and how this view naturally fits a principle of superposition. In Sec. 3 we address so-called “virtual” vs “real” processes in QM and underpinnings of the measuring processes. While Sec. 1 – 3 rest on essentially well- known facts and established views, Sec. 4, after discussing the genesis and evolution of wave-particle duality principle, considers potential future developments of this concept by asking the question: what could be behind the WPD wave facet and weighs the potential role of quantum vacuum in it.

For compactness, the following intuitive abbreviations are used for most repetitive terms: **CM** – classical mechanics, **QM** – quantum mechanics, **PS** – principle of superposition, **SE** – Shrödinger equation, **PA** – probability amplitude, **QED –** quantum electrodynamics**, WF –** wave function, **EPR** - Einstein- Podolsky-Rosen, **CI** – Copenhagen Interpretation, **WPD** – wave-particle duality.

1. Brief history and argument of “nonlocality” and “spooky action”.

The whole saga of nonlocality issue was triggered in 1936 by the paper of Einstein -Podolsky-Rosen (EPR) and then followed by the intensive discussions in 1936-1939, when it was established that QM routinely explains the long-distance correlation between non-interacting particles by the “common factor in the past”, i.e., by the initial conditions. Later, the interest to the issue resumed in connection to the Bell hidden variables theorem studies, in particular, Freedman- Clauser double decay experiments, followed by the refined measurements by the Aspect group, various spontaneous double conversion (SPDC) set ups, and many others – all invariably confirmed conservation laws at any distance. Since then to date, there exists a quite widely spread misconception that something is terribly wrong with QM, because it cannot explain long-distance correlations between entangled particles without some mysteriously infinite and instantaneous interaction, dubbed by Einstein as “spooky action”.

Before going any further, it should be noted that in contrast to a popular misperception, entanglement is to no extent an exotic phenomenon: on the contrary, it has been routinely emerging in QM’s almost centennial experience in treating molecular, atomic, nuclear, and elementary particle scattering and never caused the need for a “supernatural” nonlocality. Indeed, the physics of conservation in the entanglement can be plainly clarified by the following general analogy.
The process of a pair (or a group of particles) birth / creation can be described by some Hamiltonian, acting from t = - ∞ to t = ∞, as in the S-matrix approach, and then it looks exactly as a standard scattering process. In it the total energy, momentum, angular momentum, spin, etc. conserve, although

the components of these variables belonging to individual colliding partners change and re-distribute, forming outgoing channels, each with its own amplitude, and each channel complies strictly with conservation laws. Further, the moment the scattering potential vanishes, final amplitudes "freeze" and scattering products continue to propagate freely until hitting the detectors, which straightforwardly register the conservation laws in each and every channel, with no need for any "spooky" action. Remarkably, the similar arguments have been published by D.I. Blokhintsev as early as in 1938 (!), but since then have been merely forgotten.
After this warm-up introduction we proceed to the distributional interpretation of a wave function in the context of the superposition principle.

2. Interpretation of WFs and their superposition.

According to the initial de Broglie conjecture, WFs were deemed as some "material" waves associated with real particles. This had very much influenced the so called "Copenhagen Interpretation"(CI). When M.Born devised his Statistical Postulate, the WF became a strange hybrid of a material wave with probabilistic properties, which caused lots of troubles to CI. Among other things, it led to number of paradoxes, the most famous of which is the "collapse" of WF. However, over the years, it became clear, that WF is not a material wave, but a wave of probability, so to speak. This was among factors, that prompted Feynman to introduce his interpretation of Ψ as "probability amplitude", complex-valued function, with square modulus $|\Psi(x, t)|^2$ being a "normal" classical probability. In more precise terms, the gradual build-up of the interference picture in low-intensity beam experiments in conjunction with Born's statistical postulate lends a direct support to a view at wave function as a distribution function amplitude.

From that angle, the superposition principle represents merely a composition law of distribution functions, corresponding to individual eigen states. Therefore, in a superposition state, a dynamic variable assumes various values, each occurring with frequency generally proportional to the amplitude of corresponding eigen state in the superposition (more precisely – proportional to modulus square of wave function amplitude). In other words, under this view the measuring device does not need to make a decision of choosing among available superposing components, but rather each sample of the system / each ensemble member arrives at the measuring device in quite a specific virtual state. Rephrasing this slightly, a superposition state is a set of eigen states, each occurring commensurately to its amplitude in the superposition. We emphasize the word "virtual" above: while we do not know how exactly quantum randomness "assigns" specific values of a dynamic variable to each sample of the system, technically, as long as we operate with this "assignment" at the amplitude level (which is nothing but ordinary QM calculations), the results will be correct and consistent. To reiterate: <u>because we are unable to observe virtual events at the amplitude level, the term "assignment" should not be taken literally, as if it were implying some real process. Rather, it stands as a convenient picturing of a gradual build-up process of a distribution / wave function similarly to, say, Feynman virtual paths making up an exact transition amplitude</u>. And further, since a wave function can be routinely transformed between any pair of representations, this "assignment" is deemed happening in every possible representation which can be revealed at the measurement stage by properly tuning the equipment.

It feels quite important to avoid potential misunderstandings by commenting as follows.
The key error facilitating a nonlocal interpretation roots in an incorrect view of a superposition state and shifting a conceptual focus from the very system to the measuring device. Namely, what is typically assumed is that a superposition state is a sort of "synthetic" state with the system being somehow in all components <u>**SIMULTANEOUSLY**</u>, and it is the measuring device job to "trigger" the transition to a specific component. But that's what is precisely incorrect! According to an understanding of WF as a

distribution, superposition stands for a set of potentialities (usually, orthogonal) occurring alternately - not simultaneously! - on only one at a time basis per each ensemble member, and what remains for the measuring device is only to register it.
In more formal words, a superposition state is a set of potentialities each complying with conservation laws and occurring proportionally to its amplitude in a superposition, i.e., the WF is a distribution function in a virtual space of amplitudes.

3. "Virtual" vs "real" processes in QM and the role of measuring devices.

The term "virtual" above deserves a bit deeper clarification as the debate what's "real" vs "virtual" in QM is as old as QM itself and is caused by the QM two-level structure.
Lower, Ψ- level: according to SE, micro-particles lead their daily in and out life at the level of WFs $\Psi(x)$, that is, quantum amplitudes. Quite provisionally, we can call this level "virtual", or "underground" level, invisible to the observer with macroscopic measuring devices.
Upper, $|\Psi|^2$ – level: only occasionally, when we perform actual measurements, micro-particles step up "above the ground" to produce observable effects at the macro-level, which is manifested by $|\Psi(x)|^2$.
That two-level concept leaves certain room for diverging views and quite exotic interpretations (e.g., J. Wheeler even went as far as saying "No elementary quantum phenomenon is a phenomenon until it is observed phenomenon"). The stance of this text is a "minimal" framework based on distributional view of WFs within of statistical interpretation of QM.
We emphasize accordingly, that micro-particles lead their "virtual" life regardless and independent of whether we observe them by performing measurements. It is in that sense that Einstein once asked A. Pais "whether he really believed that the Moon existed only when he looked at it…"(!). Our answer to that is, in a sense, that the world of micro-particles is as objective as it gets at its virtual level, regardless of our measuring intervention. The virtual world is merely disconnected from the real macro-world until and unless we perform measurements, but that by no means negates its reality. (We mention here in passing that once we measure $|\Psi(x)|^2$, we can also restore $\Psi(x)$ itself - up to an arbitrary global phase factor exp(ia) - but that calls for some non-trivial translation from the $|\Psi(x)|^2$ level to the $\Psi(x)$ level). It would be decisively incorrect to think that the idea of hidden (<u>not</u> in the Bell hidden parameters sense!) life of the virtual quantum world is just an artifact of pure mathematical manipulations with a decomposition of wave functions over different eigen function systems. Quite to the contrary – this "shadow" life reveals itself via unequivocal imprints in properly set experiments.

We illustrate the manifestation of the so-called "virtual" states and transitions via two examples, namely, a) direct nuclear reactions, and b) creation of entangled pairs of photons, as in, e.g., the now classic Aspect group experiments with photon pair creation in 1980s.

In a), the projectile, say, nucleon, scatters from the target nucleus as if it were interacting only with a quasi-free nucleon, and not with the whole nucleus. An explanation comes from a simple fact, that each nucleon in the target may become momentarily "free", forming thereby a combination (free nucleon + rest of the nucleus), which contributes to the total target WF and scattering amplitude commensurately to the amplitude of this instantaneous / "virtual" jump to freedom. While this process might appear quite improbable, it nevertheless is reliably observed in the scattering cross-sections. To emphasize: it is a critical realization for the distributional interpretation of WFs that the component of the superposition, corresponding to the potentiality (free nucleon + rest of the nucleus) – as in ANY superposition – is populated by the system Hamiltonian in the Ψ – world PRIOR to any contact with a measuring device / detector. In turn, the detector performs its duty by translating the state in the Ψ – world to $|\Psi|^2$ –world.

In b) the same considerations apply . Indeed, when a pair of photons is created – it is born in one of the potentialities provided by the system per each quantum ensemble member, and because this happens locally due to some Hamiltonian, there is no problem with meeting conservation laws. And further, since the parting photons do not interact, they continue to occupy the same potentiality in the Ψ-world until they hit the detector whose sole responsibility is to register that potentiality via translating it into $|\Psi|^2$ – world. Repeating from Sec. 2: this interpretation pretends to no more than conveniently portray virtual events in Ψ – world, and as such is fundamentally different from the real default mechanism, discussed by Furry in 1936 (*W. Furry,"Note on the Quantum-Mechanical Theory of measurement" Phys. Rev, v.49, p.395,1936*), as well as from the general view of "naïve realism".

As follows from the above examples, the "virtual" level of QM is the key element in a correct understanding of the separation of responsibilities between the quantum system and measuring device, which, in turn, sheds light on the origins of the non-local interpretation. Namely, while quantum potentialities emerge specifically because of the internal interaction in the quantum system itself, and in a full compliance with the conservation laws, the role of the measuring device boils down to "publishing" what a measuring device is tuned to, albeit (!), with the unavoidable destruction of the quantum ensemble coherence. While the quantum system "creates" a random realization for every conceivable dynamic variable per each ensemble member, say, particle in the beam, a measuring device, in turn, reports the random realization depending on its tuning.

This is quite analogous to the old discussion in the Fourier-analysis of to what extent the Fourier-components of a non-harmonic signal are real, and aren't they merely created by the spectral analyzer? The answer to this is quite simple: the initial signal and its Fourier decomposition are fully equivalent, and the role of the spectral analyzer boils down to just reacting to the component ("carving" from the system) the analyzer is tuned to. Speaking somewhat loosely, eigen states participating in the superposition play the role of sort of "frequencies", to which the measuring device is tuned and reacts to. Emphasizing one more time the key word here: "reacts", but not "creates"! The "creation" job of all dynamic variables per each ensemble member (say, particle in the beam) is on a quantum system itself, via the mechanism of quantum randomness – the true "terra incognita" of QM.

Section brief summary. While a measuring device in QM typically (excluding eigen states) alters irreversibly the quantum system, it nevertheless delivers on its main function, that is, reveals the specific realization of quantum system complying with all conservation laws **just prior** to the measurement event. Say, for entangled pairs of particles with the total spin 0, the reading (↑) at one end of the pair corresponds to the state of the correlated pair (↑,↓), reading (↓) - to the state (↓,↑). In other words, quantum measurements do not create, but only measure the reality, as expected.

4. Genesis and evolution of the wave-particle duality.

So far, the exposition in this note has been resting on a firm ground of well-established facts and accepted views. In this section in reviewing the genesis and evolution of the wave-particle duality (WPD), we outline a hypothetically possible future development of WPD.

Historically, WPD outgrew from 1) the de Broglie hypothesis associating each micro-particle with the corresponding wave, and 2) experiments, demonstrating diffraction effects in scattering of photons, electrons, etc., i.e., all micro-particles. Conceptually, 1) and 2) were solidified in the Copenhagen Interpretation (CI) of WF as a metric of an individual particle, and since then WPD is generally understood as that all aspects of phenomena in quantum world can be explained either via classical, i.e., particle-like view, or wave-like view, **<u>but not both</u>**. To many, this construct appeared, and still does, as quite a formal, if not somewhat artificial, combination of two incompatibles, but one way or the other, for want of any better alternative it became a main pillar of QM vs CM philosophy. In 1927, Eddington even dubbed this hypothetical hybrid as “wavicle”. With time, however, it became clear, especially in the context of the Born statistical postulate, that 1) is not quite correct (and CI along with it), and that WFs describe not individual particles, but rather their full congregations – the so-called quantum ensembles.

Independently, but relatedly, with the development of QED at the end 1940s, there began shaping up an interest in what’s behind the wave facet of WPD. That was stimulated by a realization that vacuum is not merely an empty space, but rather a special medium, exerting subtle, but experimentally detectable footprint on quantum systems / micro-particles (e.g., Lamb shift, electron-positron pair formation, etc.). As a result, from then on there began numerous attempts to construct QM as a random motion in fluctuating vacuum fields. Various implementations of this idea would make a way too long list of related works, so we site just a few with references therein: *A.A. Sokolov (Introduction to Quantum Electrodynamics, Moscow, 1958), M. Roncadelli (Random path quantization, In: Path integrals from mev to MeV, Tutzing’92, Proceeding of the 4th Int. Conference), L. Pena, A. Cetto, A. Valdes-Hernandes (The zero-point field and the emergence of the quantum, Int. J. Mod. Phys. E, Vol. 23, No. 9, 2014), D.A. Slavnov (The wave-particle duality, Physics of Particles and Nuclei, Springer, 2015)*, among many others.

Combining both lines of thoughts, we come to realize, that the apparent diffractive behavior of micro-particles, or, more generally, the wave facet of WPD, might result from a tight coupling between quantum vacuum and micro-particles. Coming out of it is an “interference” pattern, which we have accustomed to take as a “true” interference – as if micro-particles were indeed some real waves or, at least, possessing wave properties – and what constitutes a wave facet of WPD. At will, extending Feynman ideas of rendering probabilities by means of “virtual” trajectories, one can trace the invisible vacuum hand behind the “interference” a bit more quantitatively by invoking the Feynman path integral representation. Namely, each interference probability amplitude can be portrayed as a sum over all virtual paths. In turn, each path can be viewed as furnishing the action minimum for every realization of vacuum fluctuating potential, and, therefore, recasting an interference in terms of vacuum fields. Notably, the same logic applies when connecting vacuum fluctuations with Bohm’s quantum potential in his pilot-wave picture. Incidentally, Feynman’s formulation of QM is the only successful attempt to date that boils down the “wave” appearance of quantum amplitudes to interplay of classical trajectories.

To summarize the hypothesis: the quantum vacuum acts as a huge fluctuating, but stationary and common for all ensemble particles bath, which is what becomes the key source of their apparent wave-like – and coherent – behavior. That is, a diffractive appearance is nothing but a “mirage”, masquerading the behind-the-scenes-impact of vacuum fluctuations, or, roughly speaking, a mere vacuum impact in disguise. It is instructive in this regard to make a citation from Yu. B. Rumer “Introduction to wave mechanics”, 1935 (!): “…There does not exist any analogy between the motion of a single particle and a wave. Meanwhile, quite oftentimes one speaks – being incautious – about the wave nature of a single electron, while, in fact, it should be spoken about the wave nature of the whole beam of particles”.

Section brief conclusion. Needless to say, despite an undeniable appeal of the heuristic picture above and numerous efforts in this regard, it has not been implemented so far in any convincing and experimentally supported manner. It is only the future work that will show to what extent the outlined ideas come true, but until then the WPD will retain its status of the key quantum philosophy concept.

5. Conclusions and key takeaways.

Recapitulating all discussed above: while CM is governed by the Laplace-Cauchi determinism for each individual trajectory, QM applies this principle to the entire distribution of outcomes with conservation - imposed correlations built in as initial conditions. In the absence of the real interaction, correlations do not change **by default** and there is no additional mechanism in QM responsible for maintaining these correlations. Further takeaways can be summarized as follows:

1. The major confusion arising from the CI interpretation is that it facilitates a misperception of wave functions - and individual micro-particles! - as sort of real waves, extending infinitely in space, which is in a clear contradiction with our daily experimental experience and feeds ideas of some supernatural nonlocality and the like.
2. On the contrary, the distributional interpretation emphasizes the importance of particle facet of QM: WF gives an amplitude of finding a particle at some "point" in the pertinent dynamic variable space (e.g., coordinate, momentum, angular momentum, etc.), and NOT the profile of some associated wave.
3. A fundamentally important realization is that it is not individual particles that exhibit wave features, but rather their full quantum ensemble.
4. The distributional interpretation of WF helps clarify the "kinetics" of QM: SE determines an object / state vector Ψ with projections in all representations (coordinate - Ψ(q), momentum - Ψ(p), energy - Ψ(E), etc.). Accordingly, dynamic variables in each representation change randomly from one quantum ensemble member to another, populating thereby corresponding distribution / wave function. This change is governed by "true quantum randomness" and registered - not created! - by measuring devices.
5. In QM spatial coordinates are not deterministic trajectories q(t) as in CM, but merely arguments of a distribution function amplitude (wave function) Ψ(q, t), extending over all distances, that is, they are not suitable for an understanding of long-distance correlations in a classical sense. In the meantime, those correlations for each individual potentiality immediately follow from SE. That shows how important is not to mix languages when thinking of QM effects: doing otherwise, i.e., mechanistically stereotyping QM after CM, feeds the misconception of quantum nonlocality. Not surprisingly, that very same CM-QM languages mismatch underlies seemingly paradoxical features of a two-slit diffraction and similar experiments.
6. It is worth complementing the above point with somewhat more general considerations. When a pair of photons is created – it is born locally with correlations immediately reflecting conservation laws. Then the components of the pair move freely away from each other, and because there is NO INTERACTION the correlation persists at any distance, which is reliably confirmed experimentally. The standard QM based on SE plainly explains it, but a hybrid of

classical distances and quantum potentialities / amplitudes - does not and invokes a mysterious quantum “nonlocality”. This is an instructive lesson against mixing notions from differing frameworks - classical and quantum.

Acknowledgements

It is a pleasure to thank Profs. L.D. Blokhintsev and A.Yu. Khrennikov for reviewing earlier versions of the manuscript, discussions, comments and references.

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ADDENDUM

In the forthcoming part of this note we’ll attempt to draft a rough sketch for probabilistic manipulations with complex amplitudes somehow extending a traditional probability theory.

Relatedly, let us remind that there is an alternative (to analytical formulae) way to describe quantum phenomena: namely, via quantum mechanical diagrams. The diagrams can serve not only as illustrations to phenomena itself, but also to obtain final results without tedious calculations. The diagrams are arguably very effective language for QM and their role may be paralleled to differential and integral calculus for Classical Physics. However, the classic Feynman diagrams do not necessarily prove entirely convenient for the interpretation of, say, quantum correlation effects which cause well known difficulties in understanding of QM peculiarities. For instance, Feynman diagrams have no time ordering of events and do not explicitly show the occupancy numbers of quantum states. All these are quite important for an understanding of quantum correlations. An example of the treatment of various quantum correlation effects by more convenient kinetic diagrams is given in *S.V. Gantsevich ”Phases as Hidden Variables of Quantum Mechanics”, **arXiv**, 2108.07159 (2021)*. The kinetic diagrams match one to one the corresponding analytical expressions and can substitute the latter in both discussions and / or getting the calculation results (see, e.g., *R. Katilius,S.V. Gantsevich, **Fluct.Noise Lett**.,12,#4, 1350023 (2013))*.