Nonlocality and Localizability in Quantum Mechanics

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ABSTRACT. Nonlocality of simultaneous spatial correlation of a quantum phenomenon as demonstrated in various versions of Einstein-Podolsky-Rosen type experiment reduces to nonlocality of the measurement apparatus in the sense that the eigen-wavefunctions for the apparatus are completely specified in a manner of being independent of whatever object it may measure. Nonlocality of the measurement apparatus however serves as no more than a good approximation to reality at best. The theoretical imposition of nonlocality of the measurement apparatus as an approximation is compatible with the actual locality of quantum mechanics that dispenses with an agent claiming globally simultaneous specifiability of boundary conditions, though the genuine locality of quantum mechanics has to be examined without employing the nonlocality of the measurement apparatus. The actual locality of quantum mechanics is intrinsically irreversible in its development.

RESUME. La non localité de la corrélation spatiale simultanée d'un phénomène quantique, telle qu'elle a été démontrée dans diverses versions d'expériences du type EPR, se réduit à la non localité de l'appareil de mesure, en ce sens que les fonctions propres de l'appareil sont complètement déterminées d'une manière indépendante de l'objet mesuré. Mais la non localité de l'appareil de mesure joue seulement le rôle, au mieux, d'une bonne approximation de la réalité. Le fait d'imposer théoriquement la non localité de l'appareil de mesure comme une approximation est compatible avec la localité de fait de la mécanique quantique qui permet de se passer d'un agent réclamant que les conditions aux limites puissent être spécifiées globalement simultanément, bien que la localité propre de la mécanique quantique doive être examinée sans employer la non localité de l'appareil de mesure. La localité réelle de la mécanique quantique est intrinsèquement irréversible dans son développement.

1. Introduction

There is a vexed remark [1] about the significance of the experimental observation of nonlocality in quantum mechanics especially in relation to the ubiquitous locality implied by Bell's inequality [2]. An apparent violation of Bell's inequality demonstrated in the nonlocal correlation of polarized particles [3,4] suggests that there remains some factor for raising a nonlocality in the standard framework of quantum mechanics. A candidate for nonlocality as the capacity of globally simultaneous specifiability of interacting bodies is sought in boundary conditions, for no matter-field interaction proceeds at superluminal velocities. A serious problem to be examined is now on how legitimate it would be to seek nonlocality within boundary conditions.

2. External Measurement and Nonlocality

If boundary conditions are completely controlled with unlimited precision, their nonlocality can be found within the globally simultaneous specifiability or controllability. Moreover, the measurement apparatus employed for checking such a nonlocality also constitutes a part of the boundary conditions to the object to be measured.

In order to see the contribution of measurement apparatus to boundary conditions, let us consider a controlled experiment on measuring three spin coordinates S_x, S_y and S_z of a polarized particle. Here, the eigen-wavefunction of upward oriented spin along the z-direction is ψ_z^+ satisfying $S_z\psi_z^+ = \hbar/2\cdot\psi_z^+$ and similarly $S_z\psi_z^- = -\hbar/2\cdot\psi_z^-$ for downward oriented spin, where $\hbar$ is Planck's constant divided by 2π. Accordingly, linear superposition of the wave functions ψ_z^+ and ψ_z^- will give the eigen-wavefunctions of spin polarized along the x-direction ad y-directio such as

$$\begin{cases} S_x(\psi_z^+ + \psi_z^-) = \frac{\hbar}{2}(\psi_z^+ + \psi_z^-) \\ S_x(\psi_z^+ - \psi_z^-) = -\frac{\hbar}{2}(\psi_z^+ - \psi_z^-) \end{cases}$$

$$\begin{cases} S_y(\psi_z^+ + i\psi_z^-) = \frac{\hbar}{2}(\psi_z^+ + i\psi_z^-) \\ S_y(i\psi_z^+ + \psi_z^-) = -\frac{\hbar}{2}(i\psi_z^+ + \psi_z^-). \end{cases}$$

If a beam of polarized particles is externally measured with regard to the z-component spin and if the meter-reading gives a result of being polarized 100% upward, the spin-wavefunction that has been identified will consist only of the eigen-wavefunction ψ_z^+, and none of ψ_z^-.

Furthermore, if we imagine such a situation that measurement of the z-component spin is replaced by that of the x-component spin as maintaining all of the other conditions to be the same as previously, the present interchange of measurement apparatus will affect the controllability of experiment only minimally, if at all. This interchange of measurement apparatus will let the eigen-wavefunctions $(\psi_z^+ + \psi_z^-)$ and $(\psi_z^+ - \psi_z^-)$ for the x-component spin be measurable, instead of ψ_z^+ and ψ_z^- for the z-component. Accordingly, identity

$$\psi_z^+ \equiv \frac{1}{2}(\psi_z^+ + \psi_z^-) + \frac{1}{2}(\psi_z^+ - \psi_z^-)$$

tells us that measurement of the x-component spin will give 50% being polarized upward and 50% downward along the x-direction.

Let us further suppose that the x-component measurement is followed by the z-component measurement. The spin-wavefunction to be fed into the apparatus measuring the z-component is in the form of either $(\psi_z^+ + \psi_z^-)$ or $(\psi_z^+ - \psi_z^-)$ because of the involvement of the preceding measurement of the x-component. The subsequent measurement of the z-component will give the meter-reading of 50% being polarized upward and 50% downward along the z-direction.

We thus come up with a superficial paradox or discrepancy such that a beam of polarized particles that have bee measured to be 100% polarized upward along the z-direction can be found only 50% polarized upward along the same z-direction if measurement of the x-component spin intervenes and precedes. Measurement of the z-component will give different results depending upon whether or not another measurement of the x-component spin intervenes.

However, the difference is more than being superficial. Measurement of the z-component spin implicitly sets such a boundary condition that the spin-wavefunction is a linear superposition of those that are the eigen-wavefunctions of the spin operator S_z, instead of those that are the eigen-wavefunctions of S_x or S_y. Likewise, measurement of the x-component spin of the same polarized beam lets the eigen-wavefunction of the z-component spin operator be a linear superposition of the eigen-wavefunctions of the x-component spin operator S_x.

This illustrates that the presence of successive measurements affects what each measurement identifies. Measurements determine a part of the boundary condition under which the quantum-mechanical process to be measured proceeds, especially the nature of the wavefunction in relation to how it is decomposed linearly. Measurement apparatus of any sort specifies the manner of how the wavefunction is linearly decomposed.

The capacity of measurement apparatus for specifying the manner of decomposing the wavefunction will become even more evident if several measurements take place simultaneously at different spatial locations.

Let us suppose a hypothetical experiment to measure the polarization vectors of two particles 1 ad 2 in three different ways : two independent measurements of polarization of each particle and a simultaneous measurement of two polarizations at the same time. When the polarization of each particle is limited to either plus or minus, the apparatus of measuring particle 1 assumes that the wavefunction $\mid 1 >$ is decomposed into two different eigen-wavefunctions as

$$\mid 1 >= u^+ \mid + > +u^- \mid - > .$$

The apparatus measuring particle 2 also assumes the decomposability

$$\mid 2 >= v^+ \mid + > +v^- \mid - > .$$

On the other hand, the apparatus that makes simultaneous measurement of two particles possible lets the two-particle wavefunction decomposed into four different eigen-wavefunctions as

$$\mid 1, 2 >= \alpha \mid +, + > +\beta \mid +, - > +\gamma \mid -, + > +\delta \mid -, - > .$$

If one chooses photons as polarized particles, it is possible to arrange the equipment so as to let

$$\mid u^+ \mid=\mid u^- \mid=\mid v^+ \mid=\mid v^- \mid= \frac{1}{\sqrt{2}}$$

and

$$\beta = \gamma = 0$$

be observed [3,4]. Then, it follows that although independent measurement of each particle gives 50% chances of being in plus-polarization and 50% chances of being in minus-polarization, there is a 100% parallel correlation of polarization between two photons if both are measured simultaneously. If photon 1 is measured to have plus-polarization, then photon 2 is simultaneously measured to have plus-polarization, and vice versa. This is in fact a simplified demonstration of EPR nonlocality.

The source of nonlocality is however not within something that would propagate at superluminal velocities. Quite to the contrary, the nonlocality is reduced to the manner of decomposing the wavefunction at the apparatus measuring two polarizations simultaneously as in the form

$$| 1, 2 >= \alpha \mid +, + > +\delta \mid -, - > .$$

The two-photon wavefunction, when linearly decomposed, does not allow individual two-photon wavefunctions other than those having a 100% parallel correlation of polarization between the two. Such a 100% correlation is an attribute of the measurement apparatus, and by no means the attribute of the measured object.

Any measurement apparatus imposes a specific boundary condition of its own on the object to be measured, especially in the manner of decomposing the impinging wavefunction into the linear superposition of the eigen-wavefunctions for the apparatus. Nonlocality exhibited in a simultaneous correlation extending over different spatial locations just shows a nonlocal property of the eigen-wavefunctions of the apparatus.

Nonlocality of simultaneous spatial correlation of a quantum phenomenon thus reduces to nonlocality of the measurement apparatus. And, nonlocality of the measurement apparatus further reduces to nonlocality of boundary conditions in general, since the apparatus constitutes a part of the boundary condition that makes the physical process to be measured take place. This reduction has successfully been demonstrated experimentally. However, the present experimental demonstration alone does not clarify how the nonlocality of measurement apparatus could be justified, if possible at all.

The nonlocality of measurement apparatus does require that the eigen-wavefunctions of the apparatus are completely specifiable at every moment even though the apparatus is allowed to interact with the object to be measured. This is a necessary consequence from the globally simultaneous specifiability of boundary conditions or their nonlocality. In fact, so long as the complete specifiability of the eigen-wavefunctions of the measurement apparatus is disturbed only infinitesimally during the interaction with the object to be measured, the measurement apparatus can remain external to the measured object as maintaining its nonlocality.

External measurement that makes the eigen-wavefunctions of the measurement apparatus completely specifiable takes its nonlocality for granted. If external measurement were a reality, then the nonlocality of measurement apparatus giving rise to the nonlocality of simultaneous spatial correlation of a quantum phenomenon would also be an undeniable physical reality. Crucial to the matter of nonlocality is whether external measurement can become more than an approximation to reality.

3. Internal Measurement and Localizability

Measurement is ubiquitous among any interacting bodies. In particular, measurement refers to a material process taking place between an arbitrary pair of interacting bodies, in which it is rather customary to call any one of the two the measurement apparatus and the other the measured object [5]. One common denominator of measurement is the capacity of generating mixed quantum states [6] in a sense that measurement irrevocably decomposes the measured object into the mixture of eigen-wavefunctions of the measurement apparatus, though the latter of which can in principle vary its own eigen-wavefunctions through the measurement process itself. Interaction between the measurement apparatus and the measured object renders any one of the two plastic enough to be influenced by the other. The manner of influencing is communicated through successive material interactions. There is no material agent to fully control and specify the manner of communication.

External measurement making the measurement apparatus external to the measured object is thus no more than a theoretical artifact. This artifact forcibly prohibits the measured object from influencing the way of measuring at the measurement apparatus especially in the manner of specifying the eigen-wavefunctions for the apparatus. Unless a prohibitive means is applied externally, the measurement apparatus remains internal to the measured object in the sense that even the manner of specifying the eigen-wavefunctions for the apparatus depends upon the interaction with the measured object.

Consequently, internal measurement that makes an arbitrary pair of interacting bodies mutually dependent is ubiquitous in physical processes. Internal measurement would reduce to external measurement only at the hypothetical limit of letting the measurement apparatus remain completely specifiable while being influenced by the measured object.

Once internal measurement receives due attention it deserves the problem of nonlocality will come to gain a new outlook because external measurement equipped with nonlocality of the measurement apparatus is refuted there. Internal measurement defies the globally simultaneous specifiability of boundary conditions and their nonlocality, otherwise it would reduce to external measurement. Even if they are admitted, boundary conditions remain indefinite in their implication and are only partially specifiable at best. Nonlocality of simultaneous spatial correlation of a quantum phenomenon imputed to nonlocality of the measurement apparatus is foreign to internal measurement.

One apparent nonlocality common to any quantum phenomenon is the conservation of energy. If globally simultaneous specifiability were available, the nonlocality of boundary coditions would let the conservation of energy be an attribute of the imposed nonlocality. However, internal measurement defies the involvement of such an external agent to impose a superficial nonlocality.

The absence of any outside agent to control and to specify every detail of the global interaction leads to lack of a material means to completely coordinate the global configuration of interaction in a unique manner. Still, the conservation of energy is observed to be empirically irrefutable. The actualized global configuration of interaction always satisfies the conservation of energy, in spite of the fact that there is no agent to simultaneously coordinate the whole configuration. Instead, internal measurement comes up as a material agent to coordinate the global configuration of interaction, though locally at a time. Uniqueness of the global configuration, however, is lacking when the coordination of interaction is run by internal measurement.

No interaction change initiated at a local region can simultaneously be communicated to the whole region. When the aftereffect of the interaction change initiated at one local region reaches its neighborhood, the interaction configuration in the latter must be so coordinated as to recover energy flow continuity as a local equivalent to the conservation of energy [5]. Successive spillover of local interaction changes for energy flow continuity thus accompanies internal measurement. Beneath this internal measurement lies the local process of materializing conservedness [7] yielded and entailed by the conservation of energy. Even if there is no external agent claiming the globally simultaneous specifiability or controllability of boundary conditions, internal measurement actualizes the global conservation of energy through the local process of materializing conservedness.

One remarkable property of the process materializing conservedness as a form of internal measurement is its intrinsic irreversibility, as will be seen below. The global configuration of interaction maintained by integrating internal measurements of local character lacks uniqueness in relation to their constituent local configurations because of the absence of the material means to simultaneously coordinate the whole configuration. Still, the conservation of energy is and has to be observed a posteriori. Actualization of something that lacks uniqueness of its occurrence in relation to all of the others points to a case of choosing one from may possibilities. The capacity of making choices is thus found to be latent in internal measurement during the transition form the possible to the actual. Intrinsic irreversibility is within the materialistic capacity of making choices enabling the actualization of something that lacks uniqueness of its occurrence, since the choice once made remains irrevocable.

Irreversibility associated with external measurement, on the other hand, is hard to visualize [8], since the quantum mechanical equation of motion, when supplemented by the globally simultaneous specifiability of boundary conditions, yields only a reversible dynamics. The reversibility of quantum mechanics can be saved at the expense of its locality, in which boundary conditions are claimed to be completely specifiable. Nonlocality of boundary conditions makes quantum mechanics reversible. However, once it is recognized that there is no material agent claiming globally simultaneous specifiability, quantum mechanics can make itself free from the overly theoretical commitment to reversible dynamics. Locality of boundary conditions necessarily makes quantum mechanics irreversible.

4. Concluding Remarks

Nonlocality of simultaneous spatial correlation of a quantum phenomenon reduces to nonlocality of the eigen-wavefunctions for the measurement apparatus. Experimental demonstration of nonlocality of the measurement apparatus is irrefutable. However, the demonstrated nonlocality is not a testimony to that there would be an agent claiming globally simultaneous specifiability and unlimited controllability over boundary conditions including even the measurement apparatus. It is of course possible and legitimate in an approximate sense to contrive such an experimental setup that the nonlocality of the measurement apparatus may be preserved to a certain extent against the measured object.

There is no question about the significance of what nonlocality experiments suggest. What does matter instead is that the demonstrated nonlocality of the measurement apparatus in experiment does not necessitate the involvement of a material agent claiming globally simultaneous specifiability.

Nonlocality of the measurement apparatus has been proved to be a good approximation to reality in many physical experiments. Locality imputed to Bell's inequality is violated within the scheme of the artificial nonlocality of the measurement apparatus. But, the present approximate nonlocality does not undermine the genuine locality asking no material agent controlling boundary conditions in a completely specifiable manner. The actual locality of quantum mechanics becomes visible when one does away with the nonlocality of measurement apparatus. In fact, one characteristic unique to the locality of quantum mechanics is its intrinsic irreversibility.

References

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