A no-go result for wave function realism

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Abstract

Wave function realism is a widely-discussed view about the ontology of quantum mechanics. According to this view, the wave function represents a real physical field in a fundamental high-dimensional space. In this paper, I argue that wave function realism is inconsistent with the realist assumption that an isolated system has a well-defined physical state.

Wave function realism is a widely-discussed view about the meaning of the wave function and the ontology of quantum mechanics (Albert, 1996, 2013; Ney and Albert, 2013; Ney, 2021). According to this view, the wave function represents a real physical field in a fundamental high-dimensional space, and the amplitude and the phase of the wave function are intrinsic properties of the points in the space. There has been a hot debate among philosophers of physics and metaphysicians relating to the pros and cons of wave function realism (see Ney and Albert, 2013; Ney, 2021 and references therein). In this paper, I will present a new no-go result for wave function realism.

Suppose there are two isolated distinguishable particles 1 and 2 being in a product state $\psi(\mathbf{r_1}) \otimes \varphi(\mathbf{r_2})$ at a given instant, where $\psi(\mathbf{r_1})$ and $\varphi(\mathbf{r_2})$ are two spatially separated (nomalized) wave functions in three-dimensional space. A local interaction can be introduced to add a global phase to the wave function of each particle. Consider two situations. One is that a local interaction is introduced in the region of $\psi(\mathbf{r_1})$, which adds a global phase θ to $\psi(\mathbf{r_1})$, and the state of the two particles becomes $e^{i\theta}\psi(\mathbf{r_1}) \otimes \varphi(\mathbf{r_2})$. The other is that a local interaction is introduced in the region of $\varphi(\mathbf{r_2})$, which adds a global phase θ to $\varphi(\mathbf{r_2})$, and the state of the two particles becomes $\psi(\mathbf{r_1}) \otimes e^{i\theta}\varphi(\mathbf{r_2})$.

According to wave function realism, the wave function of this two-particle system is a physical field in a fundamental six-dimensional space, and the phase of the wave function is a property of each point $(\mathbf{r_1}, \mathbf{r_2})$ in this space. This means that the two post-interaction wave functions $e^{i\theta}\psi(\mathbf{r_1}) \otimes \varphi(\mathbf{r_2})$ and $\psi(\mathbf{r_1}) \otimes e^{i\theta}\varphi(\mathbf{r_2})$ represent the same field, and this field is different from the field represented by the original wave function $\psi(\mathbf{r_1}) \otimes \varphi(\mathbf{r_2})$.

Now I will derive a no-go result for wave function realism. Assume that each isolated particle has a well-defined physical state. There are two possibilities for the changes of the physical states of the two particles in the above two situations. The first possibility is that the local interaction that adds a global phase to the wave function of each particle does not change the physical state of the particle. In this case, the two wave functions $\psi(\mathbf{r_1}) \otimes \varphi(\mathbf{r_2})$ and $e^{i\theta}\psi(\mathbf{r_1}) \otimes \varphi(\mathbf{r_2})$ or $\psi(\mathbf{r_1}) \otimes e^{i\theta}\varphi(\mathbf{r_2})$ will represent the same physical state. Note that the Schrödinger equation ensures that a local interaction with one isolated particle does not change the wave function of another isolated particle and its physical state (represented by its wave function).[1] This is inconsistent with wave function realism, according to which two wave functions that differ in the global phase represent different fields or physical states.

The second possibility is that the local interaction that adds a global phase to the wave function of each particle changes the physical state of the particle.[2] In this case, the post-interaction physical states of the two particles in the above two situations, which are represented by the wave functions $e^{i\theta}\psi(\mathbf{r_1}) \otimes \varphi(\mathbf{r_2})$ and $\psi(\mathbf{r_1}) \otimes e^{i\theta}\varphi(\mathbf{r_2})$, will be different. This is inconsistent with wave function realism either. Since the above two possibilities exhaust all possibilities, this indicates that wave function realism and our initial realist assumption are incompatible. In other words, an isolated particle cannot have a well-defined physical state in wave function realism.

This analysis also reveals an issue of underdetermination for wave function realism. According to wave function realism, the product state of two isolated particles such as $\psi(\mathbf{r_1}) \otimes \varphi(\mathbf{r_2})$, which represents a physical field in a six-dimensional space, is fundamental, while the wave function of each particle is not fundamental but emergent. When omitting the global phase, this view is indeed possible, since the product state of two isolated particles can be uniquely decomposed into two wave functions by the position coordinates. However, the global phase is real and cannot be omitted for wave function realism. This raises an issue of underdetermination. That is: the global phase of the product state of two isolated particles does not uniquely determine the global phase of the wave function of each particle. Then, given a wave function of the two particles, we cannot determine the wave

[1] There may also exist other hidden variables besides the wave function, and they may change or not change under the interaction. In this paper, the psi-ontic view is assumed, and the physical state denotes the part of the physical state which is represented by the wave function.

[2] This means that the global phase is real. For a recent discussion of the reality of the global phase see Schroeren (2022), Wallace (2022) and Gao (2022).

function of each particle. For example, there are infinitely many product states of two isolated particles whose global phases are θ, and three of them are $e^{i\theta}\psi(\mathbf{r_1}) \otimes \varphi(\mathbf{r_2})$, $\psi(\mathbf{r_1}) \otimes e^{i\theta}\varphi(\mathbf{r_2})$ and $e^{i\theta/2}\psi(\mathbf{r_1}) \otimes e^{i\theta/2}\varphi(\mathbf{r_2})$.

To sum up, I have argued that wave function realism is inconsistent with the realist assumption that an isolated system such as an isolated particle has a well-defined physical state. The question is whether the rejection of this realist assumption is reasonable for a realist view such as wave function realism. I think the answer is negative. An isolated system by definition is independent of other systems and should have its own intrinsic properties or physical state for a realist view. Moreover, admitting only the whole physical state of all isolated systems will also lead to a new nonlocal effect, namely a local interaction with one isolated system will have an instantaneous nonlocal influence on all other isolated systems, no matter how far away they are in our three-dimensional space. This nonlocal effect can hardly be explained either. It remains to be seen if wave function realists can find a plausible way to justify the rejection of the realist assumption.

References

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