The wave function and particle ontology

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Abstract

We argue that when assuming (1) the wave function is a representation of the physical state of a single system; (2) the wave function of an N-body system describes N physical entities; and (3) each triple of the 3N coordinates of a point in configuration space that relates to one physical entity represents a point in ordinary three-dimensional space, the physical entities described by the wave function are particles, and these particles move in a discontinuous and random way.

In quantum mechanics, the wave function of an N-body system is a mathematical function defined in a 3N-dimensional configuration space. We assume that (1) the wave function is a representation of the physical state of a single system; (2) the wave function of an N-body system describes N physical entities, which have respective masses and charges as indicated by the mass and charge parameters in the Schrödinger equation for the system; (3) each triple of the 3N coordinates of a point in configuration space that relates to one physical entity represents a point in an ordinary three-dimensional space. The first assumption is a common assumption in most realistic alternatives to quantum mechanics, and it is also supported by some arguments (Aharonov and Vaidman 1993; Aharonov, Anandan and Vaidman 1993; Pusey, Barrett and Rudolph 2012; Gao 2013a, 2013b). The other two assumptions seem obvious when considering the many-body Schrödinger equation and its Galilean invariance, and they are also supported by some arguments (Monton 2002; Lewis 2004). In this paper, we will analyze the existing form of the physical entities described by the wave function under these assumptions.

A direct consequence of the above assumptions is that the N physical entities described by the wave function of an N-body system exist in the region of space where the wave function is not zero, and do not exist in the region of space where the wave function is zero. The question is: In what

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form? For simplicity, we consider a two-body system whose wave function is defined in a six-dimensional configuration space. We first suppose the wave function of the system is localized in one position $(x_1, y_1, z_1, x_2, y_2, z_2)$ in the configuration space of the system at a given instant. This wave function can be decomposed into a product of two wave functions which are localized in positions (x_1, y_1, z_1) and (x_2, y_2, z_2) in our ordinary three-dimensional space, respectively. According to the above assumptions, this wave function describes two independent physical entities, which are localized in positions (x_1, y_1, z_1) and (x_2, y_2, z_2) in our three-dimensional space, respectively, and which have respective masses, say m_1 and m_2 (as well as charges Q_1 and Q_2 etc), respectively.

Now suppose the wave function of the two-body system is localized in two positions $(x_1, y_1, z_1, x_2, y_2, z_2)$ and $(x_1^{'}, y_1^{'}, z_1^{'}, x_2^{'}, y_2^{'}, z_2^{'})$ in the configuration space of the system at a given instant. This is a so-called entangled superposition state, which can be generated from a non-entangled state by the time evolution of the system[1]. According to the above analysis, the wave function of the two-body system being localized in position $(x_1, y_1, z_1, x_2, y_2, z_2)$ in configuration space means that physical entity 1 with mass m_1 and charge Q_1 exists in position (x_1, y_1, z_1) in three-dimensional space, and physical entity 2 with mass m_2 and charge Q_2 exists in position (x_2, y_2, z_2) in three-dimensional space. Similarly, the wave function of the two-body system being localized in position $(x_1^{'}, y_1^{'}, z_1^{'}, x_2^{'}, y_2^{'}, z_2^{'})$ in configuration space means that physical entity 1 exists in position $(x_1^{'}, y_1^{'}, z_1^{'})$ in three-dimensional space, and physical entity 2 exists in position $(x_2^{'}, y_2^{'}, z_2^{'})$ in three-dimensional space. Moreover, according to the above consequence of the three assumptions, the wave function of the two-body system being localized in both positions $(x_1, y_1, z_1, x_2, y_2, z_2)$ and $(x_1^{'}, y_1^{'}, z_1^{'}, x_2^{'}, y_2^{'}, z_2^{'})$ in configuration space means that these two situations both exist in certain form.

An obvious existent form is that physical entity 1 exists in both positions (x_1, y_1, z_1) and $(x_1^{'}, y_1^{'}, z_1^{'})$, and physical entity 2 exists in both positions (x_2, y_2, z_2) and $(x_2^{'}, y_2^{'}, z_2^{'})$. However, the above consequence also requires that the physical entities described by their wave function do not exist in the region of space where the wave function is zero. Therefore, when physical entity 1 exists in (x_1, y_1, z_1), physical entity 2 cannot exist in $(x_2^{'}, y_2^{'}, z_2^{'})$, and when physical entity 1 exists in $(x_1^{'}, y_1^{'}, z_1^{'})$, physical entity 2 cannot exist in (x_2, y_2, z_2), or vice versa. In other words, the wave function that describes this existent form should be localized in four positions $(x_1, y_1, z_1, x_2, y_2, z_2)$, $(x_1^{'}, y_1^{'}, z_1^{'}, x_2^{'}, y_2^{'}, z_2^{'})$, $(x_1, y_1, z_1, x_2^{'}, y_2^{'}, z_2^{'})$, and $(x_1^{'}, y_1^{'}, z_1^{'}, x_2, y_2, z_2)$ in the configuration space of the system. Therefore, this existent form, which seems to be the only possible form, is not possible.

It seems that there is a dilemma here; for the above entangled superposi-

[1]The existence of entangled states has also been confirmed by experiments.

tion state, the superposition requires that the two situations corresponding to its two branches exist at the same time, while the entanglement rejects this[2]. The key to finding the way out of the dilemma is to realize that the superposition does not require the two situations must exist at the same time at a precise instant, as the wave function of a quantum system at a given instant represents either the physical state of the system at the precise instant (like the position of a classical particle) or the limit of the time-averaged state of the system in an arbitrarily short time interval around the instant (like the standard velocity of a classical particle). For the latter case, the above two situations only need to exist "at the same time" during an arbitrarily short time interval. This is indeed possible.

Concretely speaking, the situation in which physical entity 1 is in (x_1, y_1, z_1) and physical entity 2 is in (x_2, y_2, z_2) exists in one part of continuous time, and the situation in which physical entity 1 is in $(x_1^{'}, y_1^{'}, z_1^{'})$ and physical entity 2 is in $(x_2^{'}, y_2^{'}, z_2^{'})$ exists in the other part. The restriction is that the temporal part in which each situation exists cannot be a continuous time interval during an arbitrarily short time interval; otherwise the wave function describing the state in the time interval will be not the original superposition of two branches, but one of the branches, according to the above consequence. This means that the set of the instants when each situation exists is not a continuous set but a discontinuous, dense set. At some discontinuous instants, physical entity 1 with mass m_1 and charge Q_1 exists in position (x_1, y_1, z_1), and physical entity 2 with mass m_2 and charge Q_2 exists in position (x_2, y_2, z_2), and at other discontinuous instants, physical entity 1 exists in position $(x_1^{'}, y_1^{'}, z_1^{'})$, and physical entity 2 exists in position $(x_2^{'}, y_2^{'}, z_2^{'})$. By this way of time division, the above two situations exist "at the same time" during an arbitrarily short time interval[3].

This way of time division also implies a strange picture of motion for the involved physical entities. It is as follows. Physical entity 1 with mass m_1 and charge Q_1 jumps discontinuously between positions (x_1, y_1, z_1) and $(x_1^{'}, y_1^{'}, z_1^{'})$, and physical entity 2 with mass m_2 and charge Q_2 jumps discontinuously between positions (x_2, y_2, z_2) and $(x_2^{'}, y_2^{'}, z_2^{'})$. Moreover, they jump in a precisely simultaneous way. When physical entity 1 jumps from position (x_1, y_1, z_1) to position $(x_1^{'}, y_1^{'}, z_1^{'})$, physical entity 2 must jump from position (x_2, y_2, z_2) to position $(x_2^{'}, y_2^{'}, z_2^{'})$, or vice versa. In the limit situation where position (x_2, y_2, z_2) is the same as position $(x_2^{'}, y_2^{'}, z_2^{'})$, physical entities 1 and 2 are no longer entangled, while physical entity 1 with mass m_1 and charge Q_1 still jumps discontinuously between positions (x_1, y_1, z_1)

[2]Note that the existence of this dilemma does not depend on the second assumption, namely that the wave function of an N-body system describes N physical entities, but only depend on the third assumtion, which requires that a point in the configuration space of a two-body system corresponds two points in real space.

[3]Moreover, the measure of each set of instants relates to the modulus squared of the wave function in the corresponding branch (Gao 2013a).

and $(x_1^{'}, y_1^{'}, z_1^{'})$. This means that the picture of discontinuous motion also exists for one-body systems. Since quantum mechanics does not provide further information about the positions of the physical entities at each instant, the discontinuous motion described by the theory is also essentially random.

The above analysis can be extended to an arbitrary entangled wave function for an N-body system. Since each physical entity is only in one position in space at each instant, it may well be called particle. Here the concept of particle is used in its usual sense. A particle is a small localized object with mass and charge etc, and it is only in one position in space at an instant. Moreover, the motion of these particles is not continuous but discontinuous and random in nature, and especially, the motion of entangled particles is precisely simultaneous. By a more detailed mathematical analysis of random discontinuous motion of particles (Gao 2013a), it can be further argued that the wave function of an N-body system provides a description of the state of random discontinuous motion of N particles, and in particular, the modulus squared of the wave function gives the probability density that the particles appear in certain positions in space[4].

To sum up, we have argued that the three assumptions, namely (1) the wave function is a representation of the physical state of a single system; (2) the wave function of an N-body system describes N physical entities; and (3) each triple of the 3N coordinates of a point in configuration space that relates to one physical entity represents a point in ordinary three-dimensional space, imply particle ontology, and moreover, the motion of particles is essentially discontinuous and random.

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[4] At a deeper level, the wave function may represent the instantaneous property of the particles that determines their random discontinuous motion. For a many-particle system in an entangled state, this property is possessed by the whole system. This also means that the wave function does not provide a complete description of the instantaneous state of a quantum system, which also includes the instantaneous positions of the particles of the system in space. However, different from usual hidden variables theories, the change of the position of each particle is essentially random and discontinuous. In some sense, we may say that the motion of particles is "guided" by their wave function in a probabilistic way. Note also that this picture of random discontinuous motion of particles does not provide a direct solution to the well-known measurement problem.

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