Against the field ontology of quantum mechanics

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Abstract

It has been widely thought that the ontology of quantum mechanics is real, physical fields. In this paper, I will present a new argument against the field ontology of quantum mechanics by analyzing one-body systems such as an electron. First, I argue that if the physical entity described by the wave function of an electron is a field, then this field is massive and charged. Next, I argue that if a field is massive and charged, then any two parts of the field in space will have gravitational and electromagnetic interactions, while the existence of such self-interactions for an electron contradicts quantum mechanics and experimental observations. This poses a serious difficulty for the field ontology of quantum mechanics. Third, I argue that a particle ontological interpretation of the wave function may avoid the difficulty by providing a plausible explanation of the non-existence of self-interactions. According to this explanation, the wave function of an electron is a description of the state of the random motion of the electron as a particle, and in particular, the modulus squared of the wave function gives the probability density that the electron appears in every possible position in space. Finally, I answer a major objection to the explanation of the non-existence of self-interactions in terms of particle ontology.

1 Introduction

The field ontology of quantum mechanics has been a popular position among philosophers of physics (Ney and Albert, 2013). In Bohm's theory, the wave function is usually regarded as either a real, physical field in a fundamental high-dimensional space (Bell, 1987, p.128; Albert, 1996, 2013, 2015), or a multi-field in three-dimensional space (Forrest, 1988, ch.5; Belot, 2012; Huberrt and Romano, 2018), or reduced local fields in three-dimensional space governed by a revised Schrödinger equation (Norsen, 2010). In Everett's theory, spacetime state realism has been proposed (Wallace and Timpson, 2010;

Wallace, 2012, ch.8; Swanson, 2018). According to this view, the fundamental ontology of quantum mechanics consists of a state-valued field evolving in four-dimensional spacetime. In collapse theories, the mass density ontology is a popular view (Ghirardi, Grassi and Benatti, 1995; Ghirardi, 1997, 2016; Allori et al, 2008). According to this view, "what the theory is about, what is real 'out there' at a given space point x, is just a field, i.e. a variable $m(x,t)$ given by the expectation value of the mass density operator $M(x)$ at x." (Ghirardi, 2016).[1]

Despite of the differences between these field ontologies for a many-body system, they are essentially the same for an isolated one-body system such as an electron. In this case, the spatial state of an electron is described by a wave function defined in three-dimensional space at a given instant, $\psi(x)$. According to these field ontologies of quantum mechanics, the electron is a field spreading throughout the three-dimensional space, whose state at every point is described by the amplitude and the phase of the wave function at the point. We may also say that the density of the field in position x is $|\psi(x)|^2$. According to the mass density ontology of collapse theories, the density is matter density, whose value in each position x is $|\psi(x)|^2 m$, where m is the mass of the electron.

There have been a few obections to the field ontologies of quantum mechanics, such as the objections to wave function realism (Monton, 2002, 2006, 2013; Lewis, 2004, 2013, 2016; Maudlin, 2013; Gao, 2017, ch.7, Chen, 2017), the objections to spacetime state realism (Arntzenius, 2012, ch.3; Baker, 2016; Ismael and Schaffer, 2016; Norsen, 2016), and the objections to the mass density ontology (Myvold, 2018). In this paper, I will present a new argument against the field ontology by analyzing one-body systems such as an electron. There are two reasons for doing this way. First, the analysis will be simpler. Second, if the field ontology for one-body systems turns out to be untenable, then all field ontologies of quantum mechanics will be problematic in spite of their differences for many-body systems.

This paper is organized as follows. In Section 2, I argue that if the physical entity described by the wave function of a one-body quantum system such as an electron is a field, then this field is massive and charged. Moreover, the mass and charge density of the field in each position x at a given instant t is $|\psi(x,t)|^2 m$ and $|\psi(x,t)|^2 Q$, respectively, where $\psi(x,t)$ is the wave function of the system, and m and Q are the mass and charge of the system, respectively. In Section 3, I argue that if a field is massive and charged, then any two parts of the field in space will have gravitational and electromagnetic interactions with each other, while the existence of such self-interactions for an isolated quantum system contradicts quantum mechanics

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[1] According to Allori et al (2014, p.331-2), "the matter that we postulate in GRW$_M$ and whose density is given by the m function does not ipso facto have any such properties as mass or charge; it can only assume various levels of density", and thus the mass density should be replaced by the matter density.

and experimental observations. This poses a serious difficulty for the field ontology of quantum mechanics. In Section 4, I argue that a particle ontological interpretation of the wave function may explain the non-existence of self-interactions and thus avoid the difficulty. According to this interpretation, the wave function of an electron is a description of the state of the random motion of the electron as a particle, and in particular, the modulus squared of the wave function gives the probability density that the electron appears in every possible position in space. In Section 5, I analyze a major objection to the explanation of the non-existence of self-interactions in terms of particle ontology and answer it. Conclusions are given in the last section.

2 The field for an electron is massive and charged

In this section, I will argue that if the wave function of a one-body quantum system such as an electron represents a physical field in our three-dimensional space, then the field is massive and charged.

Consider the Schrödinger equation for a quantum system with mass m and charge Q in an external electrostatic potential $\varphi(x)$:

$$i\hbar\frac{\partial\psi(x,t)}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi(x,t) + Q\varphi(x)\psi(x,t), \tag{1}$$

where $\psi(x,t)$ is the wave function of the system. The electrostatic interaction term $Q\varphi(x)\psi(x,t)$ in the equation suggests that the field described by $\psi(x,t)$ has electrostatic interaction with the external potential in all regions where the term is not zero. The existence of electrostatic interaction with an external potential in a given region means that there exists an electric charge distribution in the region, which has the efficiency to interact with the electrostatic potential and is responsible for the electrostatic interaction. Therefore, it seems that if the wave function $\psi(x,t)$ represents a field, then the field is charged in all regions where $\psi(x,t)$ is nonzero. Similarly, the field is also massive in all regions where $\psi(x,t)$ is nonzero (when considering the Schrödinger equation for a quantum system in an external gravitational potential).

The mass and charge distributions of a charged quantum system such as an electron manifest more directly during a protective measurement (Aharonov and Vaidman, 1993; Aharonov, Anandan and Vaidman, 1993; Gao, 2014, 2017). Consider an ideal protective measurement of the charge of the above quantum system in an infinitesimal spatial region dv around x_n. This is equivalent to measuring the following observable:

$$A = \begin{cases} Q, & \text{if } x_n \in dv, \\ 0, & \text{if } x_n \notin dv. \end{cases} \tag{2}$$

During the measurement, the wave function of the measuring system, $\phi(x,t)$, will obey the following Schrödinger equation:

$$i\hbar\frac{\partial\phi(x,t)}{\partial t} = -\frac{\hbar^2}{2m'}\nabla^2\phi(x,t) + k\frac{Q'\cdot|\psi(x_n,t)|^2 dvQ}{|x-x_n|}\phi(x,t), \tag{3}$$

where m' and Q' are the mass and charge of the measuring system, respectively, and k is the Coulomb constant. It can be seen from this equation that the property of the measured system in the measured position x_n that has the efficiency to influence the measuring system is $|\psi(x_n,t)|^2 dvQ$, the effective charge there (when the wave function $\psi(x,t)$ represents a real field). This is also the result of the protective measurement, $\langle A\rangle = |\psi(x_n,t)|^2 dvQ$. When $v \to 0$ and after performing measurements in sufficiently many regions V, we can find that the measured system has a charge distribution in the whole space, and the charge density in each position x is $|\psi(x)|^2 Q$.[2]

Can one deny the existence of the charge distribution of an electron when assuming the electron is a field? I think the answer is negative. Consider a situation in which the wave function of an electron is localized in two widely-seperated regions and the above protective measurement is made in one region. If there exists no charge in the measured region which is responsible for the deviation of the trajectory of the wavepacket of the charged measuring system there, then either the deviation is lack of an explanation or a new physical entity existing elsewhere (which is different from the field described by the wave function) and a new dynamics for the entity (which is different from the Schrödinger equation) need to be introduced for a realist explanation of the deviation. But if the field ontology is complete as in Everett's theory and collapse theories, then there is no room for the new physical entity. Besides, even if in Bohm's theory in which the field ontology is incomplete, the additional Bohmian particles do not provide an explanation for the deviation; no matter where the Bohmian particle of the electron is, the deviation is the same. Thus, if there is a physical entity that is responsible for the deviation of the trajectory of the wavepacket of the charged measuring system in the measured region, it must be the field which is charged in the region (when assuming the field ontology).

To sum up, I have argued that if the physical entity described by the wave function of a one-body quantum system such as an electron is a field, then this field is massive and charged. Moreover, the mass and charge density of the field in each position x at a given instant t is $|\psi(x,t)|^2 m$ and $|\psi(x,t)|^2 Q$, respectively, where $\psi(x,t)$ is the wave function of the system, and m and Q are the mass and charge of the system, respectively.[3]

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[2] Similarly, we can protectively measure another observable $B = \frac{\hbar}{2mi}(A\nabla + \nabla A)$. The measurements will tell us the measured system also has an electric flux distribution in space, and the electric flux density in position x is $j_Q(x) = \frac{\hbar Q}{2mi}(\psi^*\nabla\psi - \psi\nabla\psi^*)$. These results can also be generalized to a many-body system (Gao, 2017).

[3] For a more detailed analysis of the existence and origin of the mass and charge dis-

3 A puzzle for the field ontologists

A field, different from a particle, distributes throughout space at every instant. As a result, any two parts of a field in space (as two local physical entities) may have interactions with each other. In particular, if a field is massive and charged, then any two parts of the field in space will have gravitational and electromagnetic interactions with each other. As we will see below, this may lead to a serious difficulty for the field ontology of quantum mechanics.

Consider again the above example in which an electron is in a superposition of two widely-seperated wavepackets. If the wave function of an electron represents a physical field in space and the field is also massive and charged, then there will be gravitational and electromagnetic interactions between the two wavepackets. However, the existence of such self-interactions for an isolated quantum system contradicts the superposition principle of quantum mechanics (at least for microscopic systems such as electrons). Moreover, the existence of the electrostatic self-interaction for the charge distribution of an electron is incompatible with experimental observations either. For example, for the electron in the hydrogen atom, since the potential of the electrostatic self-interaction is of the same order of magnitude as the Coulomb potential produced by the nucleus, the energy levels of hydrogen atoms would be remarkably different from those predicted by quantum mechanics and confirmed by experiments if there existed such electrostatic self-interaction.

It seems that there is an obvious solution to the puzzle. One might still insist the field ontology but assume that a massive and charged field has no gravitational and electromagnetic self-interactions. After all, quantum mechanics only says that two different electrons have gravitational and electromagnetic interactions, and it does not say that there are gravitational and electromagnetic interactions between the two wavepackets of an electron. But the key point is that it is not quantum mechanics but the field ontology that may lead to the existence of gravitational and electromagnetic self-interactions, while quantum mechanics does not necessarily require the field ontology. If the wave function of an electron represents a real physical field in space, then the mass and charge distributions of the electron, which can be found by protective measurements more directly, will be real. While a real charge in one position will have interactions with the real charge in another position, no matter these charges belong to the same electron or two different electrons.

One might argue that the massive and charged field described by the wave function of an electron may be special, and it has no gravitational and electromagnetic self-interactions. But one still needs to explain why. In

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tributions of a quantum system see Gao (2017).

order that the field of an electron has interactions with the fields of other electrons but has no self-interactions, the field must be able to distinguish its mass and charge in a position from the mass and charge of another electron in the same position. In other words, the field ontology must be able to determine whether two charges belong to the same electron or two different electrons. But this seems impossible; a charge of an electron in a position and a charge of another electron in the same position have no differences at the ontological level for the field ontology.[4]

In addition, even if the field ontology can determine whether a charge in a position belongs to a particular electron, it also needs to explain why there are no interactions between two charges of an electron in two positions. This seems also impossible. The reason is that two charges, whether they belong to the same electron or two electrons, have no differences when considering the electromagnetic interactions, even though they might have differences in other aspects so that they can be distinguished. For example, in the non-relativistic domain where quantum mechanics holds, a charge always generates a potential in space, and it always reacts to the potential generated by another charge. Then, for the two charges of an electron in two positions, if they exist at the same time as the field ontology requires, one charge will generate a potential in space, and the other charge will react to the potential generated by this charge.

It is worth noting here that the laws of quantum mechanics or the Schrödinger equation can certainly distinguish an electron from another electron, but we cannot resort to the equation, but only resort to the ontology. The reason is that what we are trying to do here is just to use the ontology for the wave function to understand why the Schrödinger equation for a free electron contains no self-interaction terms.[5] Thus we cannot resort

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[4] Here there may be a response from the "wave function realist" à la Albert, who regards the wave function as a field on a fundamental $3N$-dimensional space. According to wave function realism, there is an ontological difference between mass and charge belonging to the same electron or different electrons: the fields of different electrons (which are part of one universal field) live in different dimensions/subspaces of the $3N$-dimensional space. For example, for the product state of two electrons $\phi(x_1)\psi(x_2)$, x_1 and x_2 are 3-dimensional coordinates of a different subspace of the fundamental $3N$-dimensional space. However, it seems that this difference will further increase the difficulty to explain why the charges of different electrons (which live in different subspaces) have interactions, but the charges of the same electron (which live in the same subspace) have no interactions; it is arguable that living in different spaces will prevent, not facilitate, interactions. Moreover, there have been plausible arguments supporting that the $3N$-dimensional space is actually a $3 \times N$-dimensional space, where the 3-dimensional coordinates of different electrons are the same three dimensions (Monton, 2002, 2006, 2013; Lewis, 2004, 2013, 2016; Gao, 2017; Chen, 2017). Thus it is arguable that the above ontological difference does not exist.

[5] This puzzle does not depend so much on the actual existence of the charge distribution as a property of an electron. It is essentially that according to the Schrödinger equation, each of the two wavepackets of an electron has electromagnetic interaction with another electron, but the two wavepackets of an electron, unlike two electrons, have no electromagnetic interaction.

to the Schrödinger equation in our analysis. This also means that we cannot claim an ontology is compatible with the Schrödinger equation (without self-interaction terms) without explaining why.

4 A way out

There is a possible way to distinguish one of the two wavepackets of an electron from another electron and explain why there are no interactions between the two wavepackets (with mass and charge) of an electron. It is that the two wavepackets of an electron do not exist simultaneously, but exist in different parts of the continuous time. Then there will be a difference between one of the two wavepackets of an electron and another electron; they exist in two different forms in time: the first exists only in one part of the continuous time, while the latter exists in the whole continuous time.

Moreover, since the two wavepackets of an electron do not exist simultaneously, they have no interactions with each other in the non-relativistic domain where quantum mechanics holds. In the non-relativistic domain, every interaction is instantaneous, described by a potential term in the Schrödinger equation. When one wavepacket of an electron exists in its region, it exists only in one part of the continuous time, during which the other wavepacket of the electron does not exist. Thus these two wavepackets do not interact with each other, even though they are massive and charged. On the other hand, since another electron exists in the whole continuous time, each wavepacket will still have interactions with the electron.

In order to explain why the Schrödinger equation for a free electron contains no self-interaction terms, it is required that any two parts of the charge distribution of an electron do not exist simultaneously. This means that the charge distribution of an electron is effective, generated by the motion of a discrete point charge. Concretely speaking, the charge density in each position x at each instant t, namely $-|\psi(x,t)|^2 e$, is generated by the motion of a discrete point charge $-e$ with spending time $|\psi(x,t)|^2 dvdt$ in the infinitesimal spatial volume dv around x in the infinitesimal time interval $[t, t+dt]$. At every instant there is only a localized, point-like particle with the total charge of the electron, and the charge density in each position is either zero (if the particle is not there) or singular (if the particle is there), while the time average of the density during an infinitesimal time interval around the instant gives the effective charge density $-|\psi(x,t)|^2 e$. Note that the motion of the particle is ergodic in the sense that the integral of the formed charge density in any region is equal to the expectation value of the total charge in the region.

This will lead to a particle ontology of quantum mechanics (Gao, 2017). Here the concept of particle is used in its usual sense. A particle is a small localized object with mass and charge, and it is only in one position in space at each instant. A few authors have suggested that the wave function represents a property of particles in three-dimensional space (see e.g. Monton, 2013; Lewis, 2013, 2016). But they do not give a concrete ontological picture of these particles in space and time and specify what property the property is. According to the above analysis, the wave function of an electron is a description of the state of the ergodic motion of the electron as a particle, which may be random and discontinuous, and in particular, the modulus squared of the wave function gives the probability density that the electron appears in every possible position in space. At a deeper level, the wave function may be regarded as a description of the propensity property of the electron that determines its random discontinuous motion (RDM). This particle ontological interpretation of the wave function can also be extended to many-body systems (Gao, 2017).

5 Objections and replies

There is a potential objection to the above explanation of the non-existence of self-interactions in terms of particle ontology. It is that the explanation may be invalid in the relativistic domain. In the relativistic domain, where interactions are mediated by fields propagating with the speed of light, "if a point charge performing RDM built up an electromagnetic field ..., the field would not instantaneously dissipate and could very well come to act back on the particle as it jumped through space. To put it the other way round: a particle moving more slowly than the speed of light can never catch up with its own emitted radiation, but a particle performing RDM at unlimited speed can." (Lazarovici, 2017) Then it seems that two wavepackets of an electron will also have interactions with each other even if assuming the particle ontology.[6]

Here one might answer this objection by noting that the Schrödinger equation holds true only in the non-relativistic domain, and since the above explanation is valid in this domain, we may ignore this objection concerning the relativistic domain. However, this answer is not wholly satisfactory. The reason is that we need not only to explain the non-existence of self-interaction terms in the free Schrödinger equation, but also to explain the non-existence of self-interactions between two wavepackets of an electron

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[6] Besides, one may argue that since electrostatic forces are usually understood, in the non-relativistic limit, as the field of a particle at rest, they would not come out for a particle performing RDM (Lazarovici, 2017). In my view, however, this is a misunderstanding. In (non-relativistic) classical mechanics, electrostatic forces are indeed understood as the field of a classical particle at rest. But in (non-relativistic) quantum mechanics, the corresponding state should not be the instantaneous state of the particle performing RDM, but the time-averaged state of RDM of the particle, namely the wave function of the particle (Gao, 2017). In this way, electrostatic forces may also be understood as the field of a charged particle when its spatial wave function is at rest, as required by quantum mechanics. This analysis also applies to magnetic forces for moving particles.

in the low energy regime (where there are no creation and annihilation of particles and a single electron may exist), which is an empirical fact. While in the low energy regime interactions are not instantaneous either in nature. Besides, the non-existence of self-interaction terms in the free relativistic wave equations (e.g. the Dirac equation) is also in want of an explanation.[7] Thus we still need to explain why two wavepackets of an electron have no interactions with each other when interactions are not instantaneous but mediated by fields propagating with a finite speed, the speed of light.

In order to answer the above objection, the key is to notice that when interactions are not instantaneous, there will be another system besides the original system, such as the electromagnetic field besides the electron. In this case, the original system is no longer an isolated system. Thus it is not beyond expectations that the above explanation of the non-existence of self-interactions for an *isolated* system in terms of particle ontology may be not valid for the original system. Furthermore, if there are interactions between two wavepackets of an isolated system, the interactions can only be instantaneous, since if they are not instantaneous but mediated by something propagating with a finite speed, then the system will be not an isolated system. This means that when considering the whole isolated system, the above explanation in terms of particle ontology is always valid, and this is independent of whether the system consists of subsystems and how these subsystems interact with each other (e.g. via fields propagating with the speed of light).

Here is an example. Suppose an isolated system is composed of two electrons with the gravitational and electromagnetic interactions, and the mass center of the system is in a superposition of two branches located in two spatial regions. Then, in each branch the two electrons still have the gravitational and electromagnetic interactions mediated by the gravitational and electromagnetic fields propagating with the speed of light. But there are no gravitational and electromagnetic interactions between the two branches when assuming the particle ontology, since the above explanation is valid for the whole isolated system.

It is worth emphasizing that the above explanation in terms of particle ontology does not explain the interactions between two systems, as well as the entanglement between two systems such as the entanglement between two electrons. It only explains why two wavepackets of an isolated system has no self-interactions or why the free wave equations for an isolated system has no self-interaction terms, which seems to be a mystery for the field ontologists. It has been shown that when assuming linearity of time evolution, the free Schrödinger equation can be derived in the non-relativistic limit

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[7] Note that we may ignore the self-energy of an electron here, since after the divergent self-interaction is removed by renormalization, it is a small quantity compared with the supposed self-interactions we need to analyze.

by resorting to spacetime translation invariance and relativistic invariance (Gao, 2017, ch.5). But, in order to derive the full Schrödinger equation, we need further postulates about the interactions betweem quantum systems.

6 Conclusions

It has been debated what the ontological content of quantum mechanics is. The field ontology is still a popular position among philosophers of physics. In this paper, I present a new objection to the field ontology of quantum mechanics by analyzing the mass and charge distributions of one-body systems such as an electron. It is argued that if the physical entity described by the wave function of an electron is a field, then this field is massive and charged. Furthermore, if a field is massive and charged, then any two parts of the field in space will have gravitational and electromagnetic interactions with each other, while the existence of such self-interactions for an electron contradicts quantum mechanics and experimental observations. This poses a serious difficulty for the field ontology of quantum mechanics. It is then suggested that a particle ontological interpretation of the wave function may provide a possible explanation of the non-existence of self-interactions. According to this interpretation, the wave function of an electron is a description of the state of the random motion of the electron as a particle, and in particular, the modulus squared of the wave function gives the probability density that the electron appears in every possible position in space. Finally, a major objection to this explanation is answered. The particle ontology provides a promisng alternative to the conventional field ontology when interpreting the wave function in quantum mechanics. Maybe it is time for us to take it seriously.

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