Recovering Particle Properties in Revisionary Ontologies[1]

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Abstract

In this paper, I explore the relation between actual scientific practice and conceptual interpretation of scientific theories by investigating the particle concept in non-relativistic quantum mechanics (NRQM). On the one hand, philosophers have raised various objections against the particle concept within the context of NRQM and proposed alternative ontologies such as wave function realism, Bohmian particles, mass density field, and flashes based on different realist solutions to the measurement problem. On the other hand, scientists continue to communicate, reason, and explain experimental phenomena using particle terms in the relevant regimes.

It has been explicitly argued and, for most of the time, implicitly assumed in the philosophical literature that we do not need to take scientists' particle talk seriously, and recovering position measurement of particles in our ontological accounts is sufficient to make contact with scientific practice. In this paper, I argue that although scientific discourse does not postulate a uniform and coherent ontology, it nevertheless postulates real properties. Our ontological accounts thus need to recover the various properties associated with the NRQM particle concept in scientific discourse. I show that recovering these particle properties is not trivially achievable by pointing out some particular challenges these revisionary ontologies face in the process.

I. Introduction

The ontological status of quantum particles is often questioned in conceptual inquiries of quantum physics. Philosophers have raised various objections against the particle concept based on different quantum theories including non-relativistic quantum mechanics (NRQM) and relativistic quantum field theory (RQFT). Enlightened by different realist solutions to the measurement problem (e.g. Everettian many-world theory, Bohmian mechanics, spontaneous collapse theories), philosophers have also proposed alternative ontological accounts such as wave

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function realism, Bohmian particles, and mass density field, among others.

Wallace (2020a; 2020b) raises an important question for the bulk of these discussions of quantum ontologies: they are taking a specific quantum theory, NRQM (the theory of finitely many non-relativistic particles interacting by long-distance forces), to be the target of their ontological interpretation and assume that similar treatment can be extended to more fundamental quantum theories. However, as Wallace shows, all realist solutions to the measurement problem, except the Everettian theory, face problems extending to RQFT, and all the revisionary ontologies face problems accounting for more complicated quantum theories and models beyond NRQM.

In this paper, I argue that the disconnection between these revisionary ontologies and actual scientific practice is more significant than what Wallace has presented: even if we acknowledge that these revisionary ontologies are non-fundamental but emergent entities, and they only account for the relatively small number of models and phenomena in higher-level regimes where NRQM is approximately true, they still face problems making contact with scientific practice in these regimes because of their revisionary nature.

NRQM is conventionally taken to be a quantum theory about N non-relativistic particles. In regimes where it is approximately true, the concept of a non-relativistic quantum particle is indispensable in scientists' theoretical and experimental practice: when scientists explain the theory in textbooks and classes (e.g. Griffiths and Schroeter 2018), conduct experiments and describe the results in labs and papers (e.g. Hensen 2015), and develop applications based on the theory (e.g. Jnane et al. 2022), terms such as 'particle', 'electron', and 'proton' always play a central role in the discussion.

If non-relativistic quantum particles do not exist according to the revisionary ontologies, then what are scientists talking about when they talk about particles? The consensus among philosophers seems to take a pragmatist view towards scientific discourse. The reason is compelling: scientists simply do not presuppose a unifying notion of particles. The scientific discourse always displays a mixture of classical and quantum mechanical, relativistic and non-relativistic notions of particles (Falkenburg 2007; Chakravartty 2017). However, Falkenburg also suggests that if we restrict ourselves to the small regime of non-relativistic and quantum mechanical, a list of properties associated with the particle concept can be inferred.

In this paper, I argue that the particle properties that are indispensable in scientists' theoretical reasoning and explanation are real. Any ontological account of NRQM thus needs to admit these properties in a proper way in order to recover the explanatory success scientists achieve through particle talk. By examining some major revisionary ontologies respectively, I show that the task is not trivially achievable.

Even though I'm restricting my discussion of quantum ontology to the regime of NRQM in this paper, the need to recover particle talk in scientific discourse could potentially be argued for in ontological discussions of other regimes as well. For example, Fraser (2021), after surveying various objections against the particle concept in RQFT, also recognizes the important role particle plays in the phenomenology associated with RQFT and the need for an ontological interpretation to explain particle scattering and decay experiments. For the sake of this paper, I'm only focusing on particle talk in NRQM because this is the regime where the revisionary ontologies are applicable (otherwise the arguments would be straw man) and where we can locate an approximately unifying set of particle properties from scientists' particle talk.

The paper is structured as follows. In section II, I briefly survey some major objections against a particle ontology in NRQM and introduce some major alternative ontologies that have been proposed. In section III, I argue that the indispensable particle properties postulated in scientific discourse are real and need to be accounted for by ontological accounts. In section IV, I examine a list of properties associated with the NRQM particle concept following Falkenburg (2007). In section V, I discuss how each revisionary ontology can account for the position measurements of NRQM particles. In section VI, I argue that there is an ontologically salient distinction between state-independent and state-dependent properties and an ontological account needs to recover this distinction. At last, in section VII, I examine each revisionary ontology respectively and point out some challenges they face in recovering the state-independent properties.

It is important to note that all discussions about fundamentality and emergence in this paper should be understood within the regimes where NRQM is applicable. As I have mentioned in the beginning, NRQM is approximately true in some higher-level regimes only. All ontologies of NRQM are thus emergent in physical reality. However, a concept of relative fundamentality can still be tenable between two emergent entities. For example, both atoms and molecules are emergent entities; but we can still understand the statement that atoms are more fundamental than molecules. It is in this sense that I will talk about fundamentality in this paper.

II. No place for particles in quantum theory

There are two types of objections against a particle ontology of NRQM. One is to argue that particle cannot be the most fundamental ontology of NRQM; the other one is to argue that the particle concept itself is untenable, and thus cannot be postulated either as fundamental or as emergent ontology of NRQM.

Objections of the first type usually appeal to the dynamical law in NRQM, the Schrödinger equation. Ney (2012, p. 533) argues:

"One might suggest that what quantum mechanics really describes is the evolution of a system of particles, or bits of matter… what the Schrödinger equation describes as evolving is just a system of particles over time, not some other mysterious object, the wave function… However, it is important to see why this sort of eliminativism about the wave function is ultimately untenable. It is not just that the Schrödinger equation superficially looks to just be about this thing, the wave function. Quantum mechanics has to invoke the wave function because there are certain states, what Schrödinger himself first called 'entangled states', pervasive in nature, that can only be captured by a physical theory that countenances such an entity as the wave function."

There are two different arguments here against particle as the fundamental ontology of NRQM. One is that the dynamical law of the theory, i.e., the Schrödinger equation, describes the behavior of the wave function instead of the particle. North (2013, p. 188) proposes a general principle that we "infer just that fundamental structure and ontology that is required by the dynamical laws". The idea is that dynamical laws in scientific theories presuppose the existence of certain things and describe how these things behave in physical reality. If the ontology presupposed by the dynamics does not exist at the fundamental level (within the system described by the theory), then the laws would be incorrect, or at least, we have no reason to believe the laws to be true. Following this, the wave function should be the fundamental ontology in NRQM instead of particles.

The more pressing argument, as emphasized in Ney (2012; 2015; 2021), is that for a system of two or more entangled particles, the quantum state of the entire system cannot be described by the state of each particle independently. This is called the non-separability of the quantum state (Glick and Darby 2020). Simply put, the description of the wave function contains more information about the system than the mere conjunction of the description of each particle. As a result, the wave function must be postulated to provide a full description of the system, and it must be more fundamental than particles.

The second type of objection against a particle ontology concerns the tenability of the particle concept itself. Due to the non-separability of the quantum state, one might question whether a particle still possesses the metaphysical individuality required for it to be seen as a separate entity (e.g., Esfeld 2004; Ismael and Schaffer 2020). Such objection is further strengthened by the phenomena of indistinguishable particles. According to NRQM, particles of the same kind possess completely identical qualitative properties. French and Redhead (1988) argue that indistinguishable particles violate Leibniz's (1686) Principle of the Identity of the Indiscernibles (PII): $\forall P\ (Pa \leftrightarrow Pb) \rightarrow a = b$, and thus cannot be seen as separate entities.[3]

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[3] For detailed analysis of how to interpret (PII) in the case of indistinguishable particles, see Morganti (2004), Hawley (2009) and references therein.

In summary, the consensus among philosophers of physics is that NRQM is not a theory about particles. The issue is further complicated by the measurement problem, to which different solutions lead to different versions of NRQM. Some realist solutions, such as Bohmian mechanics, simply cannot give rise to a conventional particle concept since it modifies the formalism of NRQM. Responding to these obstacles in a particle ontology, philosophers have proposed various alternative ontologies based on different realist solutions to the measurement problem. Some most discussed ones include wave function realism, Bohmian particles based on Bohmian mechanics, mass density field and flashes based on spontaneous collapse theories.

According to wave function realism, the universal wave function represents a physical field, which is the most fundamental ontology of NRQM (Albert 2013; Ney 2021). The wave function is not a field in ordinary 3-dimensional space, but a field in D-dimensional configuration space, where D/3 is the total number of particles understood in the conventional sense. Therefore, according to wave function realism, NRQM postulates a reality not in 3-dimensional space, but in D-dimensional configuration space.

Bohmian particles, mass density field, and flashes are all based on the primitive ontology (PO) approach according to which, "any satisfactory fundamental physical theory, if taken from a realist point of view, contains a metaphysical hypothesis about what constitutes physical objects, the PO, which lives in three-dimensional space or space-time and constitutes the building blocks of everything else" (Allori 2015).

In Bohmian mechanics, the PO is commonly agreed to be the Bohmian particles (Bohm 1952). Bohmian particles are in 3-dimensional space, point-sized, and always have determinate positions. Their positions are not represented by the wave function but instead given by the guiding equation (Dürr, Goldstein, and Zanghì 1992). In the rest of the paper, I refer to the particle concept in scientific discourse as 'particle', and the particle concept postulated in Bohmian mechanics as 'Bohmian particle'.

In spontaneous collapse theories (the original version is referred to as the GRW theory based on (Ghirardi, Rimini, and Weber 1986)), two proposals for PO have been given: mass density field (Ghirardi, Grassi, and Benatti 1995) and flashes (Bell 1987). The GRW theory with mass density ontology, denoted by GRWm, postulates a mass density field $m(x,t)$ for every point $x \in \mathbb{R}^3$ in space and time t defined by (Tumulka 2007; Allori et al. 2008):

$$m(x,t) = \sum_{i=1}^{N} m_i \int_{\mathbb{R}^{3N}} dq_1 \cdots dq_N \, \delta(q_i - x) |\psi(q_1, \cdots q_N, t)|^2.$$

To interpret it in particle language, the field at each spacetime point sums up the mass distribution of each particle at that point, where the mass distribution is the mass of the particle multiplied by its probability distribution at that point. The GRW theory with flash ontology, denoted by GRWf, postulates flashes that occur at the spacetime location of every spontaneous collapse of the wave function (Tumulka 2007; Allori et al. 2008).

III. Recovering particle talk by recovering particle properties

Particle talk plays an indispensable role in scientists' theoretical and experimental practice. Despite all the philosophical objections, scientists continue to communicate and reason in particle terms when conducting research in NRQM. To account for the scientific success that scientists have brought about through particle talk within the relevant regimes, our ontological theory should at least be able to answer the question (PT): *what are scientists talking about when they talk about NRQM particles?*

This question has been largely neglected in the philosophical literature. It has been explicitly argued and, for most of the time, implicitly assumed that we do not need to take scientists' particle talk seriously. I observe that this sort of sentiment mainly stems from two reasons. The first reason is that the scientific discourse in the relevant regimes fails to postulate a coherent and uniform ontology in NRQM due to the lack of a satisfying solution to the measurement problem. This failure from the scientific community leads to a consensus among most philosophers that scientific discourse does not generate any ontologically salient information. The second reason is the belief that recovering scientific discourse can be trivially achieved. Since scientific discourse mainly describes either the theoretical formalism of NRQM or the experimental results in relevant regimes, one might believe that it can be trivially recovered as long as an ontological account manages to recover both the theoretical formalism and the experimental results within the regime of NRQM.

In this section, I consider the first reason and argue that scientific discourse does generate ontologically salient information even though it does not postulate a coherent and uniform ontology in NRQM. In the next three sections, I consider the second reason and show that recovering scientific discourse in NRQM is not as trivial as some might believe.

How scientists interpret NRQM and the measurement problem has been heavily criticized by numerous philosophers. For example, Dürr, Goldstein, and Zanghì (1992, p. 892) state, "It is not at all astonishing that orthodox quantum theory, by refusing to accept configurations as part of the description of the state of a system, has led to so much conceptual confusion". Tumulka (2006, p. 3249) condemns the typical orthodox physicist who "openly condemns hidden variables as impossible, but in his heart cannot abandon them, and continues to talk as if particles had energies and angular momentum vectors." Maudlin (2007, p. 3171) raises similar concerns: "It has been a long hard struggle from the mysticism of Copenhagen back to a clear idea of what a physical ontology is.” In another paper of Maudlin’s (2010, p. 129), he points out the problem of adopting instrumentalism in the scientific community: “All of the mathematical machinery that seems to be about atoms and electrons is just part of an uninterpreted apparatus designed to predict correlations among the behaviors of the classical objects. I take it that no one pretends anymore to understand this sort of gobbledegook, but a generation of physicists raised on it might well be inclined to consider a theory adequately understood if it provides a predictive apparatus for macroscopic events, and does not require that the apparatus itself be comprehensible in any way.”

Indeed, even within the small regime of NRQM, scientists do not seem to have a clear interpretation of what the theory is representing. For example, scientists often talk about the wave-particle duality of a quantum object, which describes “whether a microscopic entity exhibits wave or particle attributes depending on the specific experimental setup” (Li et al. 2023). Scientists, especially experimentalists, often conveniently attribute wave-like or particle-like properties to a quantum system in an experimental setup, without explicitly explaining how the two *prima facie* incompatible sets of properties can be reconciled (that is, without providing an adequate solution to the measurement problem).

Chakravartty (2017) also points out that scientists do not always have a consensus on an ontological interpretation of quantum theories, even if they are engaged in the same scientific practices. Chakravartty argues that if scientists can perform their tasks equally well while committing to different ontological positions, then scientists’ ontological beliefs are irrelevant to the scientific success they have achieved.

But one should be careful about which conclusion we can reach here. It is one thing to say that scientists’ interpretations of NRQM or ontological beliefs about particles are dispensable, it is completely a different thing to say that scientists’ particle talk is dispensable. A physicist can conduct her research in atomic physics without believing that a particle exists, but it is much less likely that she can conduct her research without communicating with her colleagues via particle terms. And it is almost impossible for her to conduct her research without comprehending what other researchers mean by particle terms. Regardless of scientists' interpretations or ontological beliefs, language in the scientific practice of NRQM involves particle terms. And whether they refer to actual entities or not, these particle terms are nonetheless meaningful, and play an indispensable functional role in scientific communication.

While I agree with the authors above that scientists do not postulate a coherent and uniform interpretation or ontology for NRQM, I’m worried that some might take this fact to be a sufficient reason to disregard scientific discourse entirely. The lack of a realist solution to the measurement problem and the lack of a uniform ontology in scientific discourse leads to either attributing *prima* *facie* incompatible properties to a single ontology or postulating different ontologies in different experimental setups. However, these *properties* postulated in scientific discourse, including physical magnitudes, such as position, momentum, mass, and charge, as well as features postulated in the theory, such as the Born rule and the relevant symmetries, are crucial to understanding experimental results and achieving scientific success. In a realist interpretation of NRQM, these properties need to be meaningful and refer to real properties in the world.

Therefore, how scientific discourse generates ontologically salient information is not by postulating real ontologies, but by postulating real properties. The proper way to interpret the question (PT), so that it can be legitimately asked and answered, is that it is about particle properties in scientific discourse (PT-P): *which property do scientists refer to when they talk about a property associated with an NRQM particle?* Interpreted this way, an ontological account does not need to postulate an entity that is the carrier of all particle properties, but does need to locate all indispensable particle properties somewhere in the ontology so that scientists' particle talk does not turn out to be meaningless. For example, a revisionary ontological account can exclude electrons, but it nevertheless needs to recover the meaning for language such as 'detecting an electron' or 'electron mass m_e'. The causal agent for the detection event does not need to be identical to the carrier of the property m_e, but both need to be included in the account. It is in this way that an ontological account needs to recover scientists' particle talk.[4]

It is important to note that not all particle properties that scientists talk about need to be recovered. There might be particle properties that are dispensable as well. For instance, ontological claims such as 'particles are the most fundamental ontologies' are irrelevant to scientific practice, as argued above. What needs to be recovered is the indispensable particle properties scientists talk about in practice.

Let's consider the measurement problem again. Maudlin (1995, p.9) describes the "traditional interpretation of quantum theory" as "describing the collapses in terms of imprecise notions such as 'observation' and 'measurement'". Bell (1990, p.34) cites the following claim from (Dirac 1930, p.36), "... a measurement always causes the system to jump into an eigenstate of the dynamical variable that is being measured..." and criticizes such use of imprecise notions as "measurement" and "quantum jump". This property of "collapse" upon "measurement" is so problematic that it cannot be realistically interpreted: what kind of interaction counts as a measurement event? How do we physically understand certain interaction "causes" the system to "collapse"?

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[4] Notably, Egg (2021) argues for a slightly different position than I do here. He argues that textbook quantum mechanics indeed generates ontologically salient information, which should be interpreted with a functionalist perspective. This functional ontological information, however, is "all the ontological precision one can expect from an effective theory like QM" (p. 23). The difference between Egg's position and mine will be further discussed in the next section.

It is important to note that such problematic property of “collapse” upon “measurement” is not indispensable in scientific discourse. We see some respected physicists explicitly discuss the measurement problem, such as John Bell (1990), Steven Weinberg (2015), and Sean Carroll (2022). In recent textbooks on NRQM, Townsend (2012), for instance, does not explicitly talk about "collapse upon measurement"; Griffiths and Schroeter (2018) do use the notions of "collapse" and "measurement", but they also point out that these notions are problematic thus should not be interpreted realistically.

Wallace (2016) argues that dropping both the projection postulate and the eigenvector-eigenvalue link does not affect scientific reasoning and practice in experimentation and application. The projection postulate states that "measurement induces a stochastic transition on the state" so that immediately after the measurement, the system is in one of the eigenstates of the operator associated with the measurement; the eigenvector-eigenvalue link states that a system possesses a definite value of a quantity if and only if the system is in an eigenstate of the operator associated with the quantity. The projection postulate and the eigenvector-eigenvalue link together summarize the problematic language of "collapse upon measurement". According to Wallace, the problematic language associated with the measurement problem is not indispensable in scientific practice as other particle properties are.

Certainly, scientific discourse does not provide a specific solution to the measurement problem, just like it does not provide a specific ontological commitment in NRQM. Ontological inquiries, especially proposals of revisionary ontologies, are often discussed based on a specific solution to the measurement problem. But that should be an issue diagonal to our concern here: no matter which solution to the measurement problem an ontological account is based on, the account needs to provide an adequate interpretation of particle properties in scientific practice.[5]

In summary, I have shown that an ontological account of NRQM needs to be able to answer (PT-P) by recovering all indispensable particle properties in the scientific discourse of NRQM. An adequate answer should satisfy two requirements. The first is that it needs to be able to explain the communicative success of particle talk in scientific practice. An account of what ‘electron mass m_e’ refers to should be able to explain what information gets communicated and mutually understood in scientific discourse. The second is that it needs to assign the same truth values to sentences about particle properties as scientists do. If an account renders most sentences in scientific practice and research to be false, it can hardly be seen as a good interpretation, unless

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[5] One might argue that scientific discourse does implicitly commit to some specific solution to the measurement problem, such as the Everettian many-world theory, since it leaves the formalism unmodified (Wallace 2012). But even in that case, ontologies proposed in a different framework should be able to account for the particle properties scientists postulate in practice.

the proponents want to take the radical stand that scientific findings are false and of no value. This will be further explicated in the next section.

IV. Indispensable NRQM particle properties

I have argued that within the regimes where NRQM is applicable, any ontological theory should be able to account for the indispensable particle properties in scientific discourse. To do so, we need a more concrete analysis of these properties. Falkenburg (2007, p. 215-6), after a thorough analysis of scientific practice in particle physics, lists the following properties as the ones associated with the NRQM particle concept (QM):

(MQS)	carriers of mass m, electric charge q, and spin s,
(UNCOUP)	may be in non-interacting or uncoupled states,
(UNCORR)	their initial conditions are statistically uncorrelated,
(POINT)	pointlike in interactions,
(CONS)	subject to conservation laws,
(LOCPD)	localizable by a particle detector,
(PROB)	probabilistically determined by the Schrödinger equation,
(WAVE)	in states that superpose and interfere,
(UNPQ)	unsharp in momentum p and position q according to the uncertainty relation $\Delta p \Delta q \geq h/2$,
(PAULI)	not spatio-temporally individuated but only distinguished by their quantum states, according to Pauli's exclusion principle,
(BOUND)	able to form bound systems.

I shall remind the reader that my aim in this paper is slightly different from Falkenburg's. I do not intend to discuss whether these properties together form a coherent and uniform particle ontology. My aim is to list all the indispensable properties postulated in scientific discourse and examine whether a revisionary ontological account can recover them.

(PROB), (WAVE), and (LOCPD) together summarize the informal concept of wave-particle duality that scientists often attribute to an NRQM system: without measurement, the system tends to stay in states that superpose and interfere, displaying wave-like properties represented by the wave function; in a measurement outcome, the system appears to be localized probabilistically via the Born rule, displaying particle-like properties. The explanatory gap between wave-like properties and particle-like properties displayed by the same system before and after measurement is at the core of the measurement problem (Wallace 2016). The various realist solutions to the measurement problem have offered different interpretations of this. To mention very briefly, the Everettian interpretation suggests interpreting the wave function representationally and that the wave function can give rise to approximately particle-like properties due to decoherence and branching (Wallace 2012). Bohmian mechanics, on the other hand, suggests that the system displays particle-like properties at all times, while the wave-like properties only appear in the dynamical laws (Dürr, Goldstein, and Zanghì 1992). Spontaneous collapse theories suggest that wave-like states of a system can shift to particle-like states due to a spontaneous collapse of the wave function (Ghirardi, Rimini, and Weber 1986). Since all revisionary ontologies considered in this paper are based on a realist solution to the measurement problem, they can all recover the wave-particle duality talk in scientific discourse.

Yet, on the other hand, realist solutions to the measurement problem might face challenges to recover (CONS) or (POINT). For (CONS), energy conservation is explicitly violated in spontaneous collapse theories (Bassi, Ippoliti, and Vacchini 2005). Carroll and Lodman (2021) lay out different ways of interpreting energy conservation, and show possible energy non-conservation in the Everettian interpretation as well. (POINT) states that there can be no action-at-a-distance violating Einstein's causality, which is at odds with any interpretation that does not postulate the universal wave function in the ontology (Maudlin 2011; Esfeld and Gisin 2014).[6] As a result, even within the regimes where NRQM is applicable, we still don't seem to have a satisfying solution to the measurement problem that recovers all important properties in scientific practice. Since these problems have been largely addressed in the literature, I will not reiterate them here.

In order to understand how the rest of the properties get associated with a quantum system in scientific discourse, it is important to divide them into two categories: state-independent properties and state-dependent properties. State-independent properties are the ones that are always true of an NRQM system, and do not change over time evolution; state-dependent properties are the ones that are only true of an NRQM system associated with a specific time or time interval and can be gained or lost over time evolution.

(UNCOUP) and (UNCORR) are state-dependent properties. They are crucial assumptions for a quantum system to account for experimental success in NRQM. Almost all experimentation and application of NRQM rely on the assumption that quantum systems can be (at least approximately) isolated from their environment. That is, a quantum system can be in an approximately separable state from the rest of the world so interaction can be neglected. Consider the double-slit experiment, if the particles going through the slits are entangled with the rest of the world all the time, we

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[6] See Ney (2021, Ch. 3) for how wave function realism can preserve locality in some versions of NRQM.

would never be able to observe the interference phenomenon due to decoherence.

For (MQS), mass and charge appear as constants in the Schrödinger equation and thus are state-independent properties. The spin property is two-fold. First, the spin quantum number indicating whether a particle is spin-1/2 or spin-1 is a state-independent property just like mass and charge. Second, the spin state indicating, for instance, whether a spin-1/2 particle is in a spin-up state, a spin-down state, or a linear combination of these two, is a state-dependent property like position and momentum. The spin quantum number of a particle is represented by the dimension of the Hilbert space vector which is the value for the wave function; the spin state of a particle is represented by the numerical value of the Hilbert space vector itself.

(BOUND) is a state-dependent property represented by the wave function. (UNPQ) and (PAULI), although also can be represented by the wave function, are state-independent properties in NRQM. Like mass and charge, the uncertainty relation and permutation symmetry are constant features of an NRQM system.

It's important to note that Falkenburg (2007, p. 220-222) also provides a minimal operational concept of NRQM particle (OP), which includes only (UNCOUP), (UNCORR), (LOCPD), and (MESQ):

(MESQ) collections of mass *m*, energy *E*, spin *s*, charge *q*.

As Falkenburg also recognizes, the mismatch between (QM) and (OP) further emphasizes the problem that I have discussed in the previous section, namely that scientists do not postulate a uniform ontology in practice even within the small regime of NRQM.[7] Compared to (MQS), (MESQ) no longer postulates an entity that carries the properties of mass, charge, and spin, but only postulates "collections of empirical properties which constantly go together or bundles of properties which repeatedly appear together" (*ibid*., p. 221). Similarly, the properties that are left out in the operational concept, i.e. (POINT), (CONS), (PROB), (WAVE), (UNPQ), (PAULI), and (BOUND), are no longer required to be carried by an entity.

One might argue that recovering scientists' particle talk only requires a revisionary ontological account to recover the properties listed in (OP), which would be a much easier task than recovering all properties listed in (QM). (OP) only requires an ontological account to postulate the causal agents for position measurements of individual particles satisfying (UNCOUP), (UNCORR), and

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[7] Falkenburg (2007, pp.229-233) also discusses Wigner's (1939) definition of particles in terms of the irreducible representations of symmetry groups. Although Falkenburg's discussion only focuses on the Poincaré group in relativistic regimes, it is worth noting that there are also studies on the Galilean group in the regime of NRQM. For instance, Lévy-Leblond (1967) show that the representation theory of the Galilean group can give rise to mass and spin properties of NRQM particles. Thanks to an anonymous referee for pointing this out.

(LOCPD). (MESQ) can be located in the dynamics of the theory instead of attributed to the ontology. In the next section, I will briefly discuss how each of the revisionary ontologies can recover position measurements of particles thus recovering (OP). Then in Section VI, I will argue that recovering (OP) is not sufficient to account for the explanatory success achieved by particle talk in scientific discourse.

V. Recovering position measurements of particles

Maudlin (2007, p. 3159) originally raises a slightly different problem. He argues that the ontological interpretation of a physical theory needs to postulate local beables to make contact with the empirical evidence for the theory:

"In order to be of interest, physical theories have to make contact with some sort of evidence, some grounds for taking them seriously or dismissing them. And the acquisition of evidence by humans clearly does involve experience at some point. So it is not surprising that one might focus on how physical claims relate to experience in an attempt to get a handle on the problem of evidence… The contact between theory and evidence is made exactly at the point of some local beables: beables that are predictable according to the theory and intuitively observable as well."

Local beables, according to Bell (1987, p. 53), are those "which can be assigned to some bounded space-time region". The key to Maudlin's argument is that our empirical evidence for NRQM involves local observation and interaction. In order to empirically confirm the theory, there need to be local objects such as pointers, cameras, and computers in labs that we can make direct observations of. These objects, according to Maudlin, need to be constituted by local beables.

It is important to note that Maudlin's argument is different from my aim here. Maudlin urges the need for any ontological theory to recover macroscopic objects and explain our everyday experience with pointers, cameras, computers, tables, and cats. To explain these macroscopic objects, the ontological theory needs to postulate local beables. But Maudlin's argument does not concern what microscopic object is being measured when scientists make a position measurement of a subatomic particle, because we do not make direct observation of the microscopic object. As a result, even if Maudlin's argument is successful, it does not require an ontological theory to postulate a local beable as the causal agent for a particle detection event.

My aim here, on the other hand, is to recover the microscopic causal agent in a particle detection event. (OP) requires an ontological theory of NRQM to tell a story of what exactly is being detected in a localized region, that is, what causes the pointer to point up, or what causes the detector to display a particle position on the screen. However, this problem is simultaneously solved by responses to Maudlin's argument.

The solution for each PO account is pretty straightforward since they all postulate microscopic local beables. For Bohmian mechanics, the Bohmian particles are what get detected. They have definite positions at all times provided by the guiding equation and interact with the particle detector in a measurement event.[8] For mass density ontology in spontaneous collapse theories, the microscopic object is the smeared-out mass density field. Once it interacts and becomes entangled with the detection device, the wave function collapses and localizes the mass density field, as well as the particle position displayed on the screen. For flash ontology in spontaneous collapse theories, before the detection event, there is just the wave function. Once the wave function is entangled with the detector, the joint wave function collapses causing multiple flashes to occur, both at the spacetime location where the detection happens and on the detector screen.

The case for wave function realism is two-fold. First, a wave function realist might try to recover a position measurement directly from the subregions of the D-dimensional universal wave function. Ney (2013, p. 181) suggests, "point-sized regions of these peaks [of the wave function] correspond to slightly different (classical) ways of there being a desk there, slightly different configuration of particles that could make up a desk, among other things." The idea, also expressed by Wallace and Timpson (2010), is that the universal wave function can give rise to emergent quasi-classical 3-dimensional reality due to the process of decoherence.

However, one might find this approach unsatisfying. As emphasized by Maudlin (2007), Monton (2004), and Lewis (2013), it is not clear how the structure of the universal wave function can necessitate the existence of the emergent 3-dimensional reality that we experience. It seems equally possible for the D-dimensional wave function to give rise to a 2-dimensional world with D/2 particles, or to a 4-dimensional world with D/4 particles. Albert (2015) and Ney (2021) respond by providing two different strategies on how to recover micro-objects in 3-dimensional space roughly at the locations where scientists believe particles are.

Albert (2015) appeals to the functional role the subregions of the wave function can play in place for ordinary 3-dimensional objects. "The idea is that there are various different pieces or aspects or cross sections of this goop [the wave function] whose causal connections with one another, whose functional relations to one another, are a lot like the ones in virtue of which we have always been in the habit of picking something out as a particle, or as a chair, or as a table, or as a building, or as a person." (p. 145) The correspondence between the functional role played by a particle and the functional role played by the subregion of the wave function further explains why we seem to have detected a particle, while there really is just the wave function.

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[8] It has been argued that in certain circumstances, a detection event could occur in the absence of a Bohmian particle. See Solé (2017) and references therein. Thanks to an anonymous referee for pointing this out.

Ney (2021, Ch. 7), on the other hand, suggests that we can first recover 3-dimensionality from the configuration space using symmetries, manifested in dynamical invariances of the quantum state, then identify particles to be specific configurations of sub-regions of the wave function. Ney argues that since dynamical invariances and symmetries are only present if the wave function gives rise to a 3-dimensional world instead of other dimensionalities, the explanatory gap between the D-dimensional ontology and our 3-dimensional experience is bridged.

In summary, I take the project of recovering position measurements of particles thus recovering (OP) to be fairly satisfactory for all revisionary ontologies. It is important to note that the theoretical details underlying the particle detectors are left out in most of these discussions. In actual practice, the operational details of most particle detectors are based on quantum theories beyond the non-relativistic regime. For example, Solé (2017, p.483) argues that "there is a sense in which Bohmian mechanics is strictly speaking incompatible with the auxiliary theories underlying the operation of the which-path detector: namely, if these theories are explicitly relativistic and, therefore, they forbid non-locality". As a result, theoretical and ontological discussions in NRQM can only consider measurement at an abstract level: the ontology causally interacts with the detector resulting in a pointer or screen reading. The operational details of the detector cannot be accounted for by interpretations and ontologies of NRQM.

VI. Recovering state-independent and state-dependent properties

If recovering scientists' particle talk only requires a revisionary ontology to recover (OP), recovering position measurements of particles seems to be sufficient to meet the requirement. Although (MESQ) (i.e., mass, energy, spin, and charge) can also be measured in experiments, (OP) does not require an ontological account to postulate the bearer of these properties. They can be understood as mere parameters in the dynamics. The other properties listed in (QM) are not completely lost either. They all appear in the standard formalism of NRQM: the wave function, the Schrödinger equation, and the Born rule. Discussions on different realist solutions to the measurement problem and their corresponding ontological theories have suggested how to interpret or modify the formalism respectively.

However, I will show that recovering (OP) in a realist interpretation of NRQM is not sufficient to recover the explanatory success achieved through particle talk.[9] More specifically, I will argue that the state-independent properties, i.e., (MQS), (UNPQ), and (PAULI), need to be attributed to the ontology and cannot be located solely in the dynamics at the theoretic level of NRQM. The

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[9] Note that my argument here is restricted to realist interpretations of NRQM only. For accounts that do not interpret the formalism of NRQM realistically, recovering (OP) might be sufficient. For examples, see (Healey 2017) and (Fuchs, Mermin, and Schack 2014).

reason is that in order to recover the explanatory success in scientific discourse, an ontology also needs to stand in the *right relation* with the dynamical laws and observed phenomena.

To illustrate the idea, let's consider a simple experiment of sending a beam of electrons through a magnetic field. Macroscopic apparatus set-ups include preparing the beam of electrons by, for instance, heating a filament and preparing the magnetic field using magnets or electric currents. Macroscopic observation of particle detection is made on the detector screen and the particle path is then inferred. Theoretical explanation of the electron movement involves the dynamical law describing how a charged particle interacts with the magnetic field. But for the dynamical law to make contact with the experimental set-up, we need to have an understanding of what properties are carried by the system.

In the conventional scientific discourse, we have a theoretical understanding that heating a filament releases electrons. We understand that an electron carries a charge of $-q$ and a mass of m_e. We understand that an electron is spin-1/2. Based on these properties, the dynamical law tells us how the beam of electrons will interact with the magnetic field, confirming our inference of the electron path. In an ontology-neutral language, the system (described by the ontology) should nevertheless possess the following properties: being prepared by heating a filament; giving rise to a charge of $-q$ and a mass of m_e; giving rise to spin-1/2; interaction and correlation with the environment can be neglected; giving rise to a seeming movement of velocity $v(t)$; giving rise to the particle detection outcome. In summary, the system needs to make contact with the detection procedures in the experimental setup, and at the same time make contact with the dynamical law by supplying the necessary parameters.

While how the revisionary ontologies can explain the detection procedures is mostly addressed in the previous section, how they can supply parameters to the dynamical law is not obvious from a *prima facie* reading. Wave function realists suggest that what the particle detector detects is point-sized peaks of subregions of the wave function. But these high-dimensional peaks of the wave function do not possess properties such as mass charge, and spin. Bohmian particles are solely determined by the guiding equation, which only renders the positions of Bohmian particles. It is unclear whether Bohmian particles possess properties such as mass, charge, and spin. Mass density field and flashes based on spontaneous collapse theories do not possess properties such as charge and spin either.

Esfeld and Deckert (2018) respond to this challenge by arguing that properties such as mass and charge are simply dynamical parameters expressing how the system moves and interacts with experimental setups. These properties thus do not need to be possessed by the ontology. Egg (2021), drawing on Esfeld and Deckert's idea, regards this as a functional realism about these properties.

State-independent properties such as mass, charge, and spin are not possessed by the ontology describing what they are but are located solely in the dynamics of the ontology describing what they do.

It is certainly true that, as argued by Esfeld and Deckert, state-independent properties of particles might not be fundamentally intrinsic. The mass of an electron is one example. It becomes emergent and extrinsic to the electron once one considers the Higgs mechanism. But at the same time, the ontological picture also gets much more complicated if we extend our discussion to RQFT. In the scientific discourse of RQFT, particles are no longer the only things scientists talk about. Scientists also talk about quantum fields and particles as excitations of the fields. But the talk of distinct types of particles is well extended into the talk of distinct types of fields: according to the Standard Model, (it is talked about as if) there exists a field for each type of subatomic particle. State-independent particle properties correspond to field-theoretic properties that distinguish between different fields. Certainly, RQFT is not the fundamental theory of our physical reality either. Field-theoretic properties of different fields could very well be emergent and extrinsic to the fields as well.

But even if we acknowledge that any state-independent property associated with the NRQM particle concept could be emergent and extrinsic in the fundamental theory, locating them solely in the dynamics could still be worrisome. There is an ontologically salient difference between state-dependent and state-independent properties in a dynamical theory: state-independent properties are always true of the system, and state-dependent properties are not. In the conventional scientific discourse, state-independent properties are explained by what things are, while state-dependent properties are explained by what things do. This explanatory success will not be recovered if our ontological account does not recognize the difference.

Consider an example in chemistry, where many emergent properties are studied. Diamond and graphite are both composed of carbon (C), yet they possess very different physical properties. These different emergent properties are explained by the differences in the underlying chemical structures. Imagine an engineer looking for material to cut glasses before the discovery of chemistry. For her, a diamond being hard is a state-independent property, in the sense that there is a *reliable pattern* associating the diamond with its hardness. Later on, chemists discovered the molecular structure of diamonds which explains why they possess the distinct property of hardness. The number of carbon atoms being hard, for chemists, is a state-dependent property, but the reliable pattern between diamonds and hardness is preserved: when the carbon atoms are arranged in the isometric state, they give rise to diamonds and the property of hardness.

Now compare the property of hardness to mass m_e. This property of mass m_e should also be regarded as state-independent at the theoretic level of NRQM: there is a *reliable pattern* associating what gets emitted when heating a filament to the parameter m_e. This property becomes state-dependent when we move to RQFT and consider the Higgs mechanism: when the electron field is in a certain state interacting with the Higgs field, it gives rise to electrons and mass m_e. The worry with Esfeld and Deckert's account is that it ascribes having mass m_e to the system as state-dependent property at the level of NRQM. The reliable pattern between what is being emitted when heating a filament and the parameter m_e is not accounted for. On one hand, within the context of NRQM, whatever gets emitted when heating a filament *always* carries mass m_e in its dynamical evolution. If mass m_e is located in the dynamics like other state-dependent properties, it seems to suggest that whatever gets emitted could have evolved according to a different parameter m_f, which contradicts the theory's verdict. On the other hand, why the thing that gets emitted when heating a filament always carries mass m_e is only dynamically explained in the more fundamental theory, RQFT. The Higgs mechanism provides an explanation of which state of the system gives rise to the parameter m_e, which can then be regarded as a state-dependent property.

The general ontological picture I'm presenting is this: at every non-fundamental theoretic level from the more fundamental ones such as RQFT to the higher-level ones such as chemistry and biology, the theory always postulates a set of state-independent properties and a set of state-dependent properties for a system. State-independent properties are attributed to the system without dynamical explanation. They are simply facts about the system that are empirically discovered. State-dependent properties, in contrast, are explained by the dynamical laws. At every level, the unexplained state-independent properties might be explained by the dynamical laws at the more fundamental level and thus become state-dependent properties in the more fundamental description of the system. However, the key is that at every theoretic level, the state-independent properties need to be attributed to the emergent ontology postulated at that level.

Moreover, which property is directly measurable is diagonal to our concern here. At least for a realist interpretation of a theory, the scientific explanation of what a system is and how the system behaves cannot be reduced to mere descriptions of direct detection and measurement. The fact that the system can only be detected through some particular properties is irrelevant to the question of which property needs to be possessed by the system.

As a result, at the theoretic level of NRQM, locating the state-independent properties in the dynamics fails to explain why the ontology of NRQM *always* evolves according to a set of *fixed* parameters: it is neither explained by the dynamical state of the system nor explained by what the system is. The explanatory success in scientific discourse is lost in this ontological picture. State-independent properties need to be reliably attributed to the system. Such reliable patterns would then be explained by the dynamical states of RQFT, which give rise to the emergent ontology as well as the fixed state-independent properties in NRQM. This explains why it is not sufficient for a realist interpretation to only recover the operational particle concept (OP). (MQS), (UNPQ), and (PAULI) cannot be simply located in the dynamics but need to be attributed to the ontology.

VII. Recovering particle properties in revisionary ontologies

In the previous sections, I have argued that the success in the scientific practice of NRQM demands revisionary ontological theories to not only recover all indispensable particle properties postulated in scientific discourse but also recover the ontologically salient distinction between state-independent and state-dependent properties. In the following, I will consider some major revisionary ontologies respectively, and point out that all of them face the challenge of attributing at least some of the state-independent properties to the ontology.

i. Wave function realism

The wave function realism I consider here can also be called wave function monism, which suggests that the ontology of NRQM is just the D-dimensional universal wave function. The state-dependent properties (UNCOUP), (UNCORR), (BOUND), and spin state can be easily recovered since they are all expressed by possible states of the wave function. Among the state-independent properties, (UNPQ) can also be uncontroversially attributed to the wave function—it is simply a feature of what waves are. However, I will show that the wave function realists have not provided a satisfactory account to recover (MQS) and (PAULI).

Let's first consider the properties of (PAULI) as well as mass and charge in (MQS), and return to spin in (MQS) later. (PAULI) indicates the symmetrization of the wave function. Each group of 3-dimensional coordinates is symmetrically or anti-symmetrically correlated with some other groups of 3-dimensional coordinates. For example, if there is a total number of M electrons in the world, then there are M groups of 3-dimensional coordinates anti-symmetrically correlated with each other.

Mass and charge appear as constants in the Hamiltonian. The Hamiltonian for a N-particle system can be expressed as:

$$\hat{H} = \sum_{i}^{N} -\frac{\hbar^2}{2m_i}\nabla^2 + \sum_{i}^{N}\sum_{j}^{N} V_{ij}\left((x_i - x_j), (y_i - y_j), (z_i - z_j)\right)$$

The mass term for each particle is formally associated with each group of 3-dimensional coordinates in the wave function. The charge term appears in the interacting potential between charged particles, which is also formally associated with certain groups of 3-dimensional coordinates.

At this point, one might suggest that (PAULI), mass, and charge can all be attributed to the substructures of the universal wave function, namely the sub-fields associated with groups of 3-dimensional coordinates. While that might be true, it is not sufficient to account for these properties being state-independent at the theoretic level of NRQM. Note that (PAULI), mass, and charge are instantiated differently than (UNPQ). (UNPQ) is a property carried by the universal wave function, giving rise to the property of (UNPQ) for each 3-dimensional sub-field. But the properties of mass, charge, and (PAULI) are instead only carried by the 3-dimensional sub-fields. According to wave function realism, the 3-dimensional sub-fields are mere emergent entities that supervene solely on the universal wave function. The wave function realists are thus required to explain how properties of the universal wave function can give rise to the properties carried by the sub-fields.

In both Albert's (2015) and Ney's (2021) accounts, the universal wave function gives rise to the sub-fields solely through its dynamical properties. Albert (2015, p. 127) states, "The thing to keep in mind is that the production of geometrical appearances is—at the end of the day—a matter of dynamics". Ney (2021, p. 232) explicitly endorses this view: "I agree with Albert that the way to find three-dimensional objects in the wave function is to look at the latter's dynamical behavior rather than focusing on its state at a single time". Despite the differences between their accounts, both Albert and Ney agree that the dynamical properties of the universal wave function give rise to 3-dimensional sub-fields and their emergent properties.

As a result, although we seem to be able to attribute (PAULI), mass, and charge to the 3-dimensional sub-fields as state-independent properties, they are nevertheless only located in the dynamics of the universal wave function: it is not because of what the universal wave function is that the sub-fields carry (PAULI), mass, and charge; but it is because of how the universal wave function dynamically evolves that the sub-fields carry (PAULI), mass, and charge.

This, again, faces the problem I discussed in the previous section. The theoretical content of NRQM is not capable of explaining why the wave function always evolves according to (PAULI) as well as fixed mass and charge terms. Why a specific group of 3-dimensional coordinates in the wave function always evolves according to (anti-)symmetrization and some fixed parameters needs to be explained by what the wave function is, not what the wave function does. Therefore, locating (PAULI), mass, and charge in the dynamics of the universal wave function cannot recover the explanatory success that particle talk in scientific discourse has achieved.

One might want to suggest postulating the 3-dimensional sub-fields to be the most fundamental ontology in NRQM instead of the universal wave function. The resulting ontological picture is similar to what Teller (1986, p. 73) calls relational holism: “collections of objects have physical relations which do not supervene on the non-relational physical properties of the parts”. The tension between Teller’s view and wave function realism is due to the discrepancy between state-dependent and state-independent properties of a quantum system. Most of the state-dependent properties of the system need to be represented by the D-dimensional field due to non-separability, but most of the state-independent properties of the system need to be attributed to the 3-dimensional fields. Without committing to a dualist view postulating both, advocates from neither side have provided a satisfactory answer overcoming all conceptual obstacles.

The issue becomes more complicated when we add the spin quantum number into our consideration. Mathematically, a spin-1/2 particle can be represented by a wave function like:

$$\Psi(x,t) = \begin{pmatrix} \psi_+(x,t) \\ \psi_-(x,t) \end{pmatrix},$$

where $\psi_+(x,t)$ and $\psi_-(x,t)$ are complex scalar fields. A particle being spin-1/2 corresponds to its wave function taking values in a $\mathbb{C}^2$ Hilbert space. However, that is only the wave function for one spin-1/2 particle. If we consider the universal wave function, which is the ontology postulated in wave function realism, it takes values in a $\mathbb{C}^s$ Hilbert space, where s is the dimension of the tensor product between the spins of all particles in the world. As a result, the wave function does not possess the spin quantum number of each particle, but the total spin product of all particles in the world. This causes a more significant problem for wave function realism than (PAULI), mass, and charge: we don't have any apparent tool to divide the s-dimensional Hilbert space into each particle's spin vector space. We also don’t have any tool to associate each particle’s spin vector space to a specific group of 3 -dimensional coordinates. It turns out that we cannot even attribute the spin quantum number to a 3-dimensional sub-field as a state-independent property.

ii. Bohmian particles

For Bohmian mechanics, the ontology is the Bohmian particle. The ontological status of the wave function is rather unclear (Belot 2012). For my discussion here, I follow arguably the most popular view, which regards the wave function as nomological (Goldstein and Zanghì 2013).[10]

The state-dependent properties (UNCOUP), (UNCORR), and (BOUND) are not expressed by the guiding equation, but by the wave function. If the wave function is nomological dictating the dynamical evolution of the guiding equation, (UNCOUP), (UNCORR), and (BOUND) can be

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[10] There are worries with this nomological account of the wave function, as discussed by Belot (2012). The most prominent objection is that the wave function appears to be time-dependent, which means that we have a dynamical law that is constantly changing over time. Goldstein and Zanghì (2013) appeal to a working feature in quantum gravity where a time-independent wave function can be postulated. But before we have a mature theory of quantum gravity in hand, the status of a time-independent wave function remains unclear.

located indirectly in the dynamics of the Bohmian particles. (UNPQ) lies in the intrinsic nature of the wave function. Why an NRQM system constantly displays (UNPQ) can be arguably explained by the fact of what the nomological wave function is. However, for state-independent properties (PAULI) and (MQS), ontological accounts of Bohmian mechanics face a similar problem as wave function realism does above.

Recall that in Bohmian mechanics, the only direct descriptions of Bohmian particles are their positions provided by the guiding equation. (PAULI) and (MQS) are all located in the wave function only. Goldstein et al. (2005) suggest the possibility of postulating different species of particles in a Bohm-type theory of NRQM. However, they also recognize that their "assessment of which particles are quarks and which are electrons presumably could not be based on any sort of direct access to the particle's intrinsic nature, but rather must be based on information about the particle's behavior, reflected in the overall configuration of the particles" (p. 109). As a result, even in a Bohm-type theory that resembles scientists' talk of different species of particles, Bohmian electrons and Bohmian protons bear no difference from each other in terms of what they are, but are only different in how they behave dynamically.

As I have argued in the previous section, locating the state-independent properties in the dynamics at the theoretic level of NRQM cannot provide a satisfactory account for the explanatory success in scientific discourse. While Goldstein et al. could be right that (PAULI) and (MQS) might not be intrinsic properties, they cannot be located in the dynamics of NRQM, but only in the dynamics of a more fundamental theory, such as RQFT.

One might intend to argue that since (PAULI) and (MQS) appear in the nomological wave function, they can be seen either as features of the law or as physical constants postulated in the law. Consider, for instance, the gravitational constant postulated in Newton's law of universal gravitation and compare it to the mass term of an electron. While it is true that the gravitational constant does not describe a property of some entity, it is postulated to describe the gravitational force of interaction between two massive bodies. It is not clear how the electron mass can have the same ontological status. An electron mass term at the level of NRQM does not describe any force or interaction specifically, and it is explicitly associated with a specific Bohmian particle in the guiding equation. To say that the mass term is associated with the Bohmian particle because the law postulates so is just begging the question and bears no explanatory power.

iii. Mass density field

In most ontological discussions of the spontaneous collapse theories, the universal wave function is included in the ontology. However, philosophers in favor of the primitive ontology (PO) approach saw the need to postulate local beables in addition to the wave function and, therefore proposed the mass density field account and the flash ontology account. What is unsettled in the literature is whether the POs are as fundamental as the wave function or are merely emergent and reducible to the wave function (Lewis 2006; Egg 2017). The problem of regarding the POs as emergent is similar to the one faced by wave function monism above. As Egg (2017, Sec 3) points out, the universal wave function can only give rise to 3-dimensional POs through its dynamical properties. As a result, even if the state-independent properties (PAULI) and (MQS) can be attributed to the POs, they are nevertheless only located in the dynamics of the wave function.

Therefore, to avoid reiterating myself, I will only consider the dualist view committing to both the wave function and some PO at the fundamental level of NRQM, and discuss whether adding the POs helps resolve the conceptual obstacles that wave function monism faces.

The mass density field is a 3-dimensional field assigning a mass value to every spacetime point. State-dependent properties (UNCOUP), (UNCORR), and (BOUND) can all be expressed by possible states of the wave function. (UNCOUP) and (UNCORR) are also displayed by sub-regions of the mass density field as well. Consider a collection of particles approximately isolated from the environment in an experimental set-up: we can infer that the system is in an approximately uncoupled state with the environment based on the edges of the sub-field approaching zero. State-independent property (UNPQ) is also expressed by the wavy nature of the wave function as well as the mass density field.

For state-independent properties (PAULI) and (MQS), adding the mass density field to the ontology does not seem to help much. The function to calculate the field, which includes the mass term for each particle, should be interpreted pragmatically instead of representationally. For example, consider a system of two approximately localized particles of mass *m* close enough to each other so that the overlapping of each wave function is non-zero: the sub-region of the mass density field corresponding to this system displays two bumps of values slightly less than *m* at the locations where the particles are. But the intrinsic structure of the field does not make a distinction whether it's a system of two particles each with mass *m*, or it's a system of one particle with mass *2m*. Therefore, (MQS) and (PAULI) cannot be attributed to the whole or parts of the mass density field, but need to be located in the dynamics of the system again.

So, the dualist view committing to both wave function and mass density field does not fare better than wave function monism. One possible solution is to postulate N individual mass density fields corresponding to N NRQM particles. In this way, (MQS) and (PAULI) can be easily attributed to each individual field, and the universal mass density field can be recovered by aggregation of all the individual fields. Compared to the view that only postulates 3-dimensional wave functions proposed by Teller (1986), this dualist view has an advantage in explanatory power because it also includes the D-dimensional universal wave function in the ontology. It can thus better explain the non-separability feature displayed in state-dependent properties.

iv. Flash ontology

The dualist view committing to both wave function and flash ontology also fares no better than wave function monism. The existence of flashes is discrete over time. During the periods between each flash, there simply isn't anything besides the wave function. Consider a typical double-split experiment: before the particles hit the detection screen and the joint wave function collapses, there is simply nothing there traveling through the splits besides the wave function. As a result, both the state-dependent properties (UNCOUP), (UNCORR), (BOUND) and the state-independent properties (UNPQ), (PAULI), (MQS) need to be located in the wave function. While adding the flash ontology helps to explain local particle detections, it does not help to recover (PAULI) and (MQS) as state-independent properties. The dualist view committing to both wave function and flash ontology thus fares no better than wave function monism.

VIII. Conclusion

As we see from the previous section, all major revisionary ontological accounts face some challenges in finding the proper bearers for the state-independent properties postulated in scientific discourse within the regime of NRQM. Discussions in the literature have exclusively focused on reconciling the non-separability feature of an NRQM system and the local position measurements of particles. While that is indeed an important question requiring a lot of work, the explanatory power lying in the ontological distinction between state-dependent properties and state-independent properties has been largely overlooked.

Quantum theories, even just within the non-relativistic regimes, seem to have thrown more conceptual obstacles at us than we have realized. On one hand, state-dependent properties need to be represented by the description of the joint system while on the other hand, state-independent properties need to be attributed to separate individuals. As of today, we do not seem to have a completely satisfactory ontological account that can account for both in NRQM. One could hope that as relativistic versions of different realist solutions to the measurement problem are further developed in the future, we might have better resources to reach a more satisfactory ontological picture.

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