SORITES (ΣΩΡΙΤΗΣ), ISSN 1135-1349
http://www.sorites.org
Issue #15 — December 2004. Pp. 29-41
Ontic Vagueness in Microphysics

ONTIC VAGUENESS IN MICROPHYSICS

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> The farther physical science progresses the less can it dispense with philosophical criticism. But at the same time philosophers are increasingly obliged to become intimately acquainted with the sphere of research, to which they undertake to prescribe the governing laws of knowledge.
>
> E. Schrödinger (1957, 51)

1. Introduction

It is difficult, if not impossible to characterize vagueness without prejudging the issue in favour of one or another of the main interpretations of vagueness. Perhaps the central element in the notion is the existence of a *fuzzy boundary*.[1] Thus, defenders of the linguistic interpretation say that a term is vague when its meaning is not precise, whereas proponents of the epistemic interpretation hold that vagueness results from lack of precise knowledge. Those, on the other hand, who defend ontic or metaphysical vagueness usually take a vague object as an object whose physical properties are blurred or indeterminate. Another way of expressing this point is to say that a vague object is an object whose properties are not — as a matter of fact — all precisely specifiable or definable. It is *not* that we are uncertain whether the property applies to the object (this would be epistemic vagueness), but that there is objectively «no determinate fact of the matter whether that object exemplifies that property.»[2]

Much of the voluminous literature on vagueness is devoted to the question of whether there is, or there can be, vagueness in the world itself, as contrasted with its representation in thought or language. The current disinclination of students to answer these questions positively appears to derive from two main sources. There is, first, the weight of the classical analyses of the issue. As is well known, Frege regarded vagueness as a defect of ordinary language. Indeed, this is one of the reasons why he and virtually all the early analytic philosophers concentrated their attention to artificial languages.[3] Also, in his seminal 1923 article on vagueness, Bertrand Russell maintained that «Vagueness and precision alike are characteristics

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[1] Vagueness is also commonly characterized in terms of *borderline cases*. Here we shall focus on fuzzy boundaries, because the existence of borderline cases follows from the existence of fuzzy boundaries, whereas the converse does not seem to hold (see Keefe and Smith 1997, 15-16).

[2] Merricks (2001, 145). This paper offers particularly clear characterizations of the three main views of vagueness. For a more specific attempt to define ontic vagueness, see Sainsbury (1989).

[3] For an account of Frege's views on vagueness, see Williamson (1994, sect. 2.2).

which can only belong to a representation, of which language is an example. They have to do with the relation between a representation and that which it represents».[4] This was meant by Russell to apply also to thoughts, which he regarded as a kind of private representation. But the attribution of vagueness to the represented objects is denounced by him as an instance of the «fallacy of verbalism — the fallacy that consists in mistaking the properties of words for the properties of things».[5] Finally, Michael Dummett claimed, in a much-quoted phrase, that «the notion that things might actually *be* vague, as well as being vaguely described, is not properly intelligible».[6]

The second main source of antipathy to ontic vagueness is Gareth Evans's one-page 1978 article. On the face of it, the paper offers a formal proof that «the idea that the world might contain certain objects about which it is a *fact* that they have fuzzy boundaries», being therefore vague, is not «coherent». Not unexpectedly, the exact meaning and import of Evans's cryptic proof became the subject of hot controversy in the literature, which continues unabated to our days.[7]

In this article we shall not re-examine the classical arguments against ontic vagueness, nor discuss the details of Evans's proof. Our aim is to contribute to the debate through a philosophical analysis of some central elements of our best scientific understanding of the nature of the material world. More specifically, we shall explain in some detail why our basic theory of matter, quantum mechanics (QM), describes objects as being irreducibly vague. We shall also indicate that there are strong theoretical and experimental reasons for taking this aspect of QM as having come to stay.

2. The import of science to the debate on ontic vagueness

Vagueness has traditionally been regarded as a philosophical issue, and this is just right, since it has traditionally been associated with language and thought, and these undoubtedly are philosophical provinces. Nonetheless, philosophy has also traditionally been interested in reality, except within certain philosophical schools. Given that vagueness was brought to fore in contemporary philosophy when one of these schools dominated the philosophical scene, it

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4 P. 62, as reprinted in Keefe and Smith (1997b). In addition, Russell maintained, controversially, that all words in natural languages, even logical terms, are to some extent vague.

5 *Ibid*., p. 62. For a recent criticism of Russell's position, see Colyvan (2001). The present article can be taken as providing support to Colyvan's general criticism, as it presents a concrete, fully developed scientific case for the existence of vague objects.

6 (1975, 260), as reprinted in Dummett (1978). It is fair to remark, however, that Dummett later recanted from this strong position; see his (1981, 440).

7 For a sample of the most important attempts at clarification, see e.g. Lewis (1988), Burgess (1989) and (1990), Parsons and Woodruff (1995), Over (1989), Johnsen (1989), Keefe and Smith (1997a, 49 ff), Williamson (1994, sect. 9.2), Pelletier (1989). A different line of attack on ontic vagueness has been proposed by Sorensen (1998); for a criticism, see Markosian (2002).

is no surprise that it was, and still is, largely or exclusively taken as a linguistic or mental phenomenon.

But abhorrence to metaphysics has faded away, and the time is ripe for rehabilitating reality as a genuine philosophical subject. In the early modern period, however, philosophy gave birth to science, which has taken upon itself the task of investigating the material world. From that time on, we cannot, thus, afford to ignore what science says about the nature of the material objects. However, most of the philosophers engaged in discussing vagueness — even ontic vagueness — do not appear to recognize this point fully.

Recent analyses of ontic vagueness have focused almost exclusively on macroscopic objects, such as clouds, mountains and cats. Furthermore, when the constitution of these objects is discussed (as formed by atoms, for instance), the analysis is implicitly guided almost exclusively by theories of classical physics. Since these theories leave no place for vagueness — in the sense that, according to them, all the properties of the *elementary* constituents of matter are in principle specifiable with complete precision — this has the effect of biasing the whole discussion against ontic vagueness from the very beginning.

Thus, claims of vagueness in the material objects have been easily dismissed as merely «superficial» vagueness. On the usual (but debatable: see Chibeni 2004) assumption that the properties of the macroscopic objects supervene on the properties of their microscopic constituents, any vagueness in the former could in principle be eliminated by their theoretical reduction to the latter.

Attention to this important distinction between superficial and non-superficial, or fundamental, vagueness has been drawn by Keefe and Smith (1997a, 56-57) and Burgess (1990). Whereas the former authors do not take any position on the dispute, Burgess appears to regard superficial vagueness as genuine ontic vagueness, irrespective of what happens at the basic level. Although disagreeing with Burgess on this point, we strongly support his view that the issue of whether «the world is microscopically divisible into sharp objects … is best treated as an empirical claim» (p. 285).

Now, we obviously get different answers to this question, depending on which theory we choose. We believe that our guide here should be the *best currently available* physical theory. The fact that this theory will, like any other, be fallible does not imply that the choice is immaterial. Even if our interest is restricted to the question of whether there *can* be vague objects — as opposed to whether there actually are such objects in the world —, the theoretical choice is important. It is just silly to rely — for whatever purpose — upon a theory which is *known* to have met with refuting evidence. Curiously, this point has been largely ignored by the students of ontic vagueness. The first noticeable exception was, to our knowledge, provided by Lowe 1994.

In this article Lowe argued that a certain quantum mechanical system involving a pair of electrons constitutes a genuine instance of ontic vague *identity*. Lowe's example was, thus, directly addressed to Evan's proof.[8] Lowe's paper has generated some interesting discussion

[8] Besides offering the quantum counterexample to the proof, Lowe endeavoured, as many did before him, to locate its «flaw» by direct analysis.

in the literature.[9] Although fully agreeing with Lowe's line of inquiry, we think that he was unfortunate in the choice of his example, since it involves the thorny issue of the identity of quantum objects. Also, the whole controversy over Evans's proof piggybacks on his analysis, making the issue rather too complex. We shall not enter into this discussion here. In the following section we explain, through a general theoretical analysis, how ontic vagueness arises in QM. In section 5 we illustrate the point by offering a sample of straightforward examples of ontically vague quantum objects which do not involve the identity relation. And in section 4 we point out that certain theoretical and experimental results, made available in the second half of the twentieth century, impose forbiddingly severe constraints on any microphysical theory purporting to avoid ontic vagueness.

3. A theoretical analysis of quantum mechanics vis-à-vis the issue of ontic vagueness

Both in classical theories and in QM, the properties of objects fall into two classes: static, or state-independent properties, such as rest mass, charge and spin, and dynamic, or state-dependent properties, such as position, momentum, energy, spin components, etc. The former are always precisely definable, in both kinds of theories. Dynamic properties, on the other hand, are typically *not* sharply definable in QM, in contrast with what happens in classical theories. This fundamental difference arises from the peculiar way quantum mechanics characterizes the *states* of physical objects.

Whereas in classical mechanics the state of a particle is represented by a set of six numbers — the three components of its position and of its momentum — in quantum mechanics the pure states of an object are complex-valued functions — usually referred to as *wavefunctions* — or, more generally, vectors in a Hilbert space. In both classical and quantum mechanics the purpose of defining states is to allow the prediction of the physical properties belonging to the object. In the former theory, the specification of the state allows, in principle, the prediction of *all* the dynamical quantities of the object, such as its kinetic energy, angular momentum, etc. Quantum mechanical states, however, do *not* afford a complete value assignment to all the quantities which can legitimately be measured on and therefore, apparently, attributed to the object. It should be stressed that this holds even for the *pure* quantum states, i.e. the states embodying *maximal* information about the object. This unique situation in the history of physics is illustrated in section 5 by three simple examples.

The fact that *no* quantum mechanical state gives precise values to all the dynamical properties of quantum objects immediately leads to the suspicion that the theory is *incomplete* as a description of physical reality. This apparent incompleteness of QM is at the root of most of the intriguing features of this theory, and separated the founding fathers into two opposite camps. Led by Bohr and Heisenberg, most of them *denied* that there is anything missing in the quantum mechanical theoretical description («*position 1*»), whereas Einstein and Schrödinger insisted that the theory is, indeed, incomplete («*position 2*»). The two most powerful arguments to sustain the latter view appeared in 1935: Einstein, Podolsky and Rosen's argument concerning certain pairs of correlated quantum objects (EPR 1935) and Schrödinger's argument concerning the measurement process, known as the «cat paradox» (Schrödinger 1980).

[9] See e.g. French and Krause (1995, 1996 and 2003), Noonan (1995), Hawley (1998), Odrowaz-Sypniewska (2001), Lowe (1997 and 1999).

This is not the place to examine the controversy over the completeness of QM. We just want to explore its connections with the issue of ontic vagueness. We begin by noticing that the incompleteness view (position 2) clearly suggests an epistemic interpretation for quantum vagueness. According to this view, the lack of sharp values of physical magnitudes in QM is to be regarded a theoretical aspect only, to be eliminated through the addition of more information on the object, in the scope of a more complete theory.

The interpretation of the opposite view (position 1) is more complex. There are three general options open to the proponents of the completeness of QM:

1a) *Anti-realism:* the concept of a physically describable reality is abandoned. This stand was often taken by Bohr and his followers. The problem of ontic vagueness is thereby bypassed; the theory is meant as referring to phenomena only, not to real objects lying behind them. The lack of a complete value assignment in QM is interpreted as a trait of quantum theoretical language only.

1b) *Heisenberg's disturbance doctrine:* the objects are conceived as possessing sharp attributes only, but they are mostly «unknowable *in principle*». Due to the existence of the so-called «quantum of action», the act of observation would introduce an unavoidable and uncontrollable disturbance in the state of the objects, so that the precise values of many of their properties are always beyond our reach. The positivist doctrine (fashionable in the 1930's) would then discharge QM from the task of describing these properties. The theory should, thus, be considered complete, at least with respect to what can be *known* about reality. In this case there is no real ontic vagueness, just epistemic vagueness. The difference with respect to position 2 (incompleteness) is that now the missing information is claimed to be experimentally unobtainable.

1c) *Reality itself is fuzzy:* the attributes lacking theoretical values in QM are objectively blurred. The classical ontologies of sharp objects are replaced by a notion of reality with fuzzy objects, exactly to match what is found in the quantum formalism.

Failure to distinguish clearly these positions has often led to deep confusions in the historical debate concerning QM. In his classic 1927 article on the indeterminacy relations, for instance, Heisenberg first deduced his relations — which were to become the *locus* for discussing the failure of QM to provide a complete property assignment — from the mathematical properties of wavefunctions, and then tried to confirm them physically by the famous gamma-ray microscope thought experiment. Now, whereas the initial deduction presupposes that reality is conceived as a literal counterpart of the wavefunction (a possible way to instantiate position 1c), quantum objects being thus «wave-like» and therefore fuzzy, the microscope experiment assumes that reality is formed of more or less classical particles, with sharply defined properties, but whose precise values are claimed to lie beyond experimental determination (position 1b). In his notoriously obscure texts on the completeness of QM, Niels Bohr also intermingled elements of both the ontic and the epistemic defences of completeness (positions 1c and 1b), as well as of anti-realism (position 1a).

Now the tenability of the central thesis of this article depends on the existence of good reasons for adopting position 1c. We believe such reasons *do* exist: strong objections can be raised to all the other alternatives.

Firstly, although most of the founding fathers of QM leaned towards one type or another of anti-realism (position 1a), we hold that the abandonment of the classical realist stand in science is not forced upon us by QM, as they often assumed, and that a careful philosophical analysis of the issue favours realism instead (Chibeni 1999).

Secondly, concerning position 1b, even if positivism is taken for granted, the defence of completeness through the idea of a disturbance upon measurement has several irreparable conceptual shortcomings, as first shown by Popper in his *Logic of Scientific Discovery* (first German edition 1934). But Popper was swimming against the tide, and his criticism passed virtually unnoticed for more than two decades. It is now generally agreed, however, that his arguments were sound, and that his point can be supported by other, independent arguments as well. Details on this issue can be found elsewhere (Chibeni 2001).

Finally, we shall examine in a separate section the case against position 2 (incompleteness), as it deserves a more detailed attention.

4. Restoring ontic sharpness in microphysics?

By 1935 the completeness thesis was already prevalent, and not even EPR's and Schrödinger's powerful arguments for incompleteness changed the rapidly established orthodoxy. It is our opinion, however, that the weight of the original rebuttals to these arguments was overestimated, and that sound evidence for completeness did not arise until much later. Ironically, such evidence — which, given the analysis above, should also count as evidence for ontic vagueness — was finally obtained through a series of no-go results concerning the so-called *hidden variables* research programme, which aimed exactly to complete what was apparently missing in QM.

In the literature on the foundations of QM, the expression 'hidden variables' designates certain parameters, to be added to the quantum mechanical states in order that all measurable physical magnitudes of objects get a definite, sharp value. The first and most important *hidden variables theory* (HVT) was formulated by David Bohm in 1952. This theory is capable of reproducing all the quantum mechanical empirical predictions and, at the same time, of restoring sharpness in all the properties of quantum objects. As Bohm himself noticed, however, this achievement has a price: certain other theoretical and conceptual traits of classical theories are violated by the theory. More importantly, further theoretical and experimental research has revealed that not only Bohm's theory has to pay this price, but *any* other theory capable of completing the quantum mechanical property assignment must pay as well. We are here referring to the following three classes of results.

There is, first, a series of algebraic proofs, in the tradition of von Neumann's famous 1932 theorem, to the effect that completing the quantum states through hidden variables leads to inconsistencies (Gleason 1957, Bell 1966, Kochen and Specker 1967, Mermin 1990). Bohm's theory escapes inconsistency only by incorporating a form of «contextualism», roughly meaning that some properties assigned to the object somewhat reflects its «experimental context» in a thoroughly non-classical way.

Secondly, in 1964 John S. Bell proved that the most objectionable trait of Bohm's theory, *nonlocality*, must be present in any HVT reproducing certain quantum mechanical predictions concerning correlated, EPR-type pairs of objects.[10] These peculiar predictions have

[10] Roughly put, locality is the assumption — well backed by relativity theory — that all physical influences take finite time to propagate in space. For an exposition of the reasons that have led Einstein to maintain that this is a principle to which we should «absolutely hold fast» in physics (1949, p. 85),

subsequently been confirmed by several experiments, the most important of which being reported in Aspect et. al. (1982). *Any* empirically adequate HVT must, therefore, be non-local.

Finally, some authors succeeded, more recently, in bringing together these two classes of results, showing that the assumption of a local HVT also leads to mathematical inconsistencies (Heywood and Redhead 1983, Greenberger et al. 1989).

These results mean that although the restoration of sharpness in the dynamic properties of quantum objects is possible, as clearly shown by Bohm, the price may be too high. They form, thus, the basis of a strong argument for taking quantum mechanical fuzziness as being much more than a peculiarity of a *specific* theoretical representation of reality (QM).[11]

5. Vague quantum objects: three simple examples

The boundaries concerning which objects are regarded as vague or precise are often taken as their spatio-temporal boundaries.[12] This restriction is by no means necessary, and tends to bias the issue against ontic vagueness, especially when the theories used to analyse the notion of a material object are classical theories. It is important to bear in mind that it can be discussed, for instance, if an object possesses a definite energy, or spin component, or polarization, and these are not spatio-temporal properties.

QM offers plenty of examples of objects lacking properties of both kinds. According to QM this is indeed the *rule*, not the exception, at least in the case of the fundamental entities forming the material world, such as electrons, photons, neutrinos, protons, neutrons, quarks, etc. We shall now give three straightforward examples, taken from non-relativistic quantum mechanics. None of the conclusions drawn depends on this or other simplifications, which are made solely for the sake of mathematical simplicity.

a) Let us begin by considering the simplest example possible, that of a single particle with one degree of freedom not subject to the action of forces. Take, for instance, an electron allowed to move along a straight line, and let us concentrate on two of its dynamic properties, position and momentum (mass times velocity). At any given instant its quantum mechanical state will then be the complex-valued function of the spatial coordinate x

$$\Psi(x) = (2\pi\hbar)^{-1/2} \int_{-\infty}^{+\infty} \phi(p) \exp(ipx/\hbar)\, dp$$

see Fine 1986 and Howard 1985.

[11] French and Krause seem to be the first who have drawn attention, if only *en passant*, to the no-hidden-variables results in connection with the issue of ontic vagueness. In their (1996), for instance, they remark that «the force of Bell's Theorem lies in its generality, and it is this which renders the vagueness ontic in the sense that it is not dependent upon a *particular* representation» (p. 25). See also French and Krause 2003.

[12] See e.g. Burgess (1990, 263), Keefe and Smith (1997a, 50), Sorensen (1998).

where $\hbar$ is the reduced Plank constant, p is the momentum coordinate and $\Phi(p)$ is a complex-valued function of p. Although $\Psi(x)$ has no straightforward meaning as a «wave» in ordinary 3-d space, by the Born rule its modulus squared gives directly the probability of getting a result between x and $x + \mathrm{d}x$ in a position measurement: $\mathrm{P}(x)\mathrm{d}x = |\Psi(x)|^2\mathrm{d}x$. In typical situations, this quantity has non-zero value over large regions of space. Now if the wavefunction $\Psi(x)$ is taken as embodying maximal information on the object prior to measurement, it is unavoidable, upon a realist construal of the wavefunction, to conclude that before measurement the object lacks a precise spatial localization. In other words, on the assumption that QM is complete the above probabilities cannot be understood epistemically, i.e., as reflecting lack of precise knowledge (as they could in classical physics). Thus, if we indulge at all to consider the real object and its properties, we must think of it as something «spread» over space, and lacking a spatial boundary. The exact «shape» of this fuzzy entity will, of course, depend on $\Phi(p)$, which in turn depends on the details of the actual physical circumstances involving the object. Here, it is enough to remark that $\Phi(p)$ itself is a wavefunction, related to another property of the object, its momentum. Once again, this relation is indirect: the (generalized) Born rule says that $|\Phi(p)|^2\, \mathrm{d}p$ gives the probability of finding, in a momentum measurement, a value in the interval $[p, p + \mathrm{d}p]$. Exactly the same analysis holds for p and for x, that is, p is also typically a fuzzy property of the object. It is worth mentioning that the «amount» or «degree» of fuzziness in these two properties is precisely determined by mathematical analysis of the wavefunctions: the more «diffuse» is the object in space, the less «diffuse» it will be in momentum, and vice versa. This is just one way of analysing the contents of the Heisenberg principle. It should be clear, however, that in this interpretation the principle is not at all about «uncertainties» (as the usual name «uncertainty principle» implies), but about lack of definiteness of properties. (See Chibeni 2001 for more details on this distinction.) Notice, finally, that one of the most important unsolved problems in the foundations of QM is just to understand why and how such fuzzy properties become definite upon measurement. The proponents of the orthodox interpretation of QM famously claimed that the state transition induced by measurement (from wavefunctions such as Ψ and Φ to eigenfunctions of the measured quantity, affording precise values to it) should be introduced *ad hoc* and *post factum*. For a realist this position is totally unacceptable. He wants to understand what is really happening, in terms of physical properties and interactions; furthermore, he cannot get along with the subjectivist idea that this process is peculiar to *measurements*.

b) Our second example results from the first by considering that the object is now bounded between two impenetrable barriers, lying at $x = -a$ and $x = +a$. Although in this case too we have fuzziness in x and p, we shall concentrate our attention on another property, kinetic energy. Restricting, again, the analysis to a given instant, we have that the time-independent Schrödinger equation has two possible classes of solutions:

$$u_n(x) = (a)^{-½} \cos (n\pi x/2a) \text{ (for } n = 1, 3, 5, \ldots)$$

and

$$v_n(x) = (a)^{-½} \sin (n\pi x/2a) \text{ (for } n = 2, 4, 6, \ldots).$$

An important new feature of this example is that if the object is in one of these states (for a particular n) it will have a definite energy, given by

$$\mathrm{E} = \pi^2\hbar^2n^2/8ma^2$$

where *m* is the object's mass. Furthermore, only these values can be found in energy measurements. The energy spectrum is thus discrete, or *quantized*. Also, the above states — called the energy *eigenstates* — are stationary, i.e., if the object is put in one of them, it remains indefinitely in it, unless something interferes with the object. However, the superposition principle allows any linear combination of eigenstates as *bona fide* states. Thus, the general state of our bounded object will be

$$\phi(x) = \sum_{n=1}^{\infty} A_n u_n(x) + B_n v_n(x)$$

where A_n and B_n are complex coefficients, and where the terms $A_n u_n$ and $B_n v_n$ exist only for odd and even *n*, respectively. If more than one of the coefficients is non-vanishing, the state will not be an energy eigenstate. In this case the theory does *not* ascribe a precise energy to the object: energy becomes fuzzy. Furthermore, the state will no longer be stationary, which implies that the exact «shape» of this fuzziness will vary with time. By the Born rule we have that $| A_n |^2$ and $| B_n |^2$ give the probability of getting the corresponding energy eigenvalues in an energy measurement, when the object is in the state ϕ (*x*). Again, on the assumption of completeness these probabilities cannot be interpreted epistemically. Therefore, the energy property of the object is vague, except when the state is an energy eigenstate. As in the case of position and momentum, this vagueness disappears when an energy measurement is made, and it remains a mystery why and how this can happen.

c) For our third and last example we shall take a specifically quantum mechanical property called *spin*. The name might suggest some resemblance to the spinning movement of an ordinary body, but this suggestion is misleading. Like ordinary angular momentum, quantum spin is a vector; but contrary to the angular momentum vector, its magnitude is fixed: spin is indeed one of the static properties of elementary particles, by which they are classed. The square of the spin magnitude is conventionally written as $\mathbf{S}^2 = s\ (s + 1)\ \hbar$, where *s* is a positive integer or half-integer. Thus, for electrons, protons and neutrons, for instance, we have $s = ½$. For simplicity, one says that these are 'spin-½ particles'. One may now define a related set of properties, the *spin components*. These properties depend, of course, on the spin, but they are *dynamic* and, in contrast with the components of ordinary vectors, they are always quantized. For spin-½ objects, for instance, there are just two spin components along any spatial direction *z*: $s_z = +½\ \hbar$ and $s_z = -½\ \hbar$. Take now one of these objects, an electron, say. Its complete quantum mechanical state must include, besides a wavefunction like those of our examples (a) and (b), a «part» related to spin. Disregard, for now, the wavefunction. The spin part of the state is represented by a vector in a two-dimensional Hilbert space (notice that this is *not* the spin vector!). For any direction *z*, two states are of special interest: the eigenstates of s_z, associated with the eigenvalues $+½\ \hbar$ and $-½\ \hbar$. These can be abstractly designated by $|+\rangle_z$ and $|-\rangle_z$. Thus, if the electron is in state $|+\rangle_z$, its spin component along *z* is $+½\ \hbar$; if it is $|-\rangle_z$, this property has the value $-½\ \hbar$. There is no vagueness here. If however, as allowed by the superposition principle, we take a state which is not one of these eigenstates then the spin component becomes blurred. In fact, a general spin state for a spin-½ object can be written as

$$|\Xi\rangle = \alpha\ |+\rangle_z + \beta\ |-\rangle_z$$

where α and β are complex coefficients. When none of these coefficients is zero, the state is such that there *is* ontic vagueness in the property s_z. Once again, the modulus squared of the coefficients gives the probabilities of getting the results $+\frac{1}{2}\hbar$ or $-\frac{1}{2}\hbar$ in a measurement of s_z, and these probabilities are not related to our ignorance as to the real properties of the object, on the orthodox assumption of completeness.

6. Conclusion

After arguing that what science tells us about matter should be taken into account in the debate on ontic vagueness, we remarked that the philosophers' current disinclination to believe in vague objects is partly due to their implicit adherence to superseded classical theories. We showed, both by a general theoretical analysis and by some concrete examples, that our best contemporary theory on the structure of mater, quantum mechanics, clearly ascribes fuzzy properties to objects. The examples were chosen so as to avoid several unnecessary complications inherent in the example proposed by Lowe in his much-discussed 1994 article. Furthermore, we pointed out that several theoretical and experimental results in microphysics afford very strong evidence for the existence of vague objects, as they prove that any theory purporting to restore sharpness in the properties of quantum objects will meet with severe constraints.

We stress that our case for ontic vagueness obviously presupposes a commitment to at least a mild version of scientific realism. But, as we remarked in section 3, QM or, more generally, microphysics does not represent a direct threat to this epistemological stand. In particular, we do not think Putnam is right in holding that quantum vagueness indicates that «something seems to be wrong with metaphysical realism» (1983, 274). Here, we fully agree with French and Krause, who hold, to the contrary, that «one way to maintain a form of realism in the quantum context is to take vagueness seriously».[13] We would go even further than these authors, and say that this is the *best* way of introducing realism in microphysics.[14] If, for good physical and methodological reasons, we shun contextual, nonlocal HVTs, we should accept the challenge of devising an ontology for the micro-world which takes at face value what QM says, and this includes vagueness.

Given the discouragement imposed on a whole generation of students by the leaders of the orthodox, «Copenhagen» interpretation of QM, it comes as no surprise that the search for a quantum ontology is still «in its infancy» (Krause 2000, 164). However, some progress has been made in recent decades, and it is only to be hoped that further research will shed more light on this challenging issue.

Acknowledgement

I would like to thank Mark Colyvan for his detailed and useful comments on a previous version of this article.

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[13] French and Krause (1996, footnote 1).

[14] A clear, if bizarre, alternative would be the so-called many-worlds interpretation of QM; see Geroch 1984 and other papers in the same issue of *Noûs* for more details.

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