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Schrödinger's microbe: implications of coercing a living organism into a coherent quantum mechanical state

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Abstract Consideration of the experimental activities carried out in one discipline, through the lens of another, can lead to novel insights. Here, we comment from a biological perspective upon experiments in quantum mechanics proposed by physicists that are likely to feasible in the near future. In these experiments, an entire living organism would be knowingly placed into a coherent quantum state for the first time, i.e. would be coerced into demonstrating quantum phenomena. The implications of the proposed experiment for a biologist depend to an extent upon the outcomes. If successful (i.e. quantum coherence is achieved and the organism survives after returning to a normal state), then the organism will have been temporarily in a state where it has an unmeasurable metabolism—not because a metabolic rate is undetectable, but because any attempt to measure it would automatically bring the organism out of the state. We argue that this would in essence represent a new category of cryptobiosis. Further, the organism would not necessarily retain all of the characteristics commonly attributed to living systems, unlike the currently known categories of cryptobiosis. If organisms can survive having previously been in a coherent state, then we must accept that living systems do not necessarily need to remain in a decoherent state at all times. This would be something new to biologists, even if it might seem trivial to physicists. It would have implications concerning the physical extremes organisms can tolerate, the search for extraterrestrial life, and our philosophical view of animation.

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There is much potential for scientific advancement in interdisciplinary research. However, it is rare for research to be truly interdisciplinary; and so as researchers, we should be watchful for developments in other areas of science that may influence our own. In this article, we discuss what is likely to be just such a development: the implications for biology of specific experiments proposed by physicists. In essence, the proposals are to coerce a living organism (such as a tardigrade—a water dwelling extremophile) into behaving as a coherent quantum object (e.g. Romero-Isart et al. 2010). Whilst there is no apparent theoretical reason that such experiments would not work from a physical perspective—rather, it is a matter of finessing the relevant experimental technology—the implications of the experimental outcomes from a biologist's point of view have yet to be fully considered. Here, after outlining some relevant physics and biology, we discuss the implications of such an experiment for the study of living systems.

Quantum theory and the concept of decoherence

A key conceptual and philosophical challenge, during the development of quantum mechanics, has been that it is full of strange phenomena that do not intuitively describe the reality we perceive directly around us at a macroscopic scale. Instead, the world we perceive at the macroscopic scale appears to behave more closely in accordance with classical Newtonian mechanics. This challenge can be resolved via the interpretation that macroscopic systems are in what physicists call a 'decoherent' state, as opposed to a state that is 'coherent' i.e. one which clearly exhibits quantum phenomena (Zurek 1991, 2003). To expand: quantum mechanical phenomena demonstrably hold in laboratory conditions on very small scales for particle systems that are isolated from their environment, and are consequently described by Schrödinger's wave equation. Such particle systems can evolve into a coherent state that is characterized by a wave function, and cannot be considered to actually exist in any one physical state (e.g. being localized to a specific position in space). Rather, all that can be said is that, if measured, the particle system would be found to be in one of various physical states, with probabilities of being found in each state determined by the particle systems 'wave function'. Before measurement, the system can thus be thought of as being in a superposition of multiple possible states at the same time, although it is hard to visualize what this might actually look like. If a measurement is taken of such a particle system, then the probability of the system being recorded in any one of these physical states is related to the squared amplitude of the wave function for that state. The act of measurement, which necessarily involves the particle system interacting with some other system (e.g. the experimental apparatus required to take the measurement), causes the wave function to 'collapse' into one of these single, decoherent, physical states.

As a hypothetical example, imagine a tardigrade that was at an unknown location: if the tardigrade was in a decoherent state, then an observer could locate it by attempting to measure its position. Subsequently, the observer could legitimately describe the tardigrade as having had a defined position in space immediately prior to measurement. But if it were in a coherent quantum state, this would mean it was in a "superposition of states", or, spread out over numerous locations at the same time, with a probability of being found at each. The act of observing the coherent tardigrade (i.e. interacting with it) would have caused its wave function to collapse, with the result that it would decohere and subsequently become localized to a specific point in space (Fig. 1).

In systems we perceive as exhibiting classical behavior, such as most macroscopic systems, the majority of the quantum information about the system is already lost as a result of interactions with the environment ("measurement" being just one form of interaction with the environment). That is to say, the wave function describing such systems is constantly being collapsed into a single decoherent state as a result of these interactions (Zurek 1991). A decoherent system is indistinguishable from a system behaving deterministically, as described by classical mechanics, which is why macroscopic systems built from components small enough to experience quantum effects don't exhibit this behaviour. For

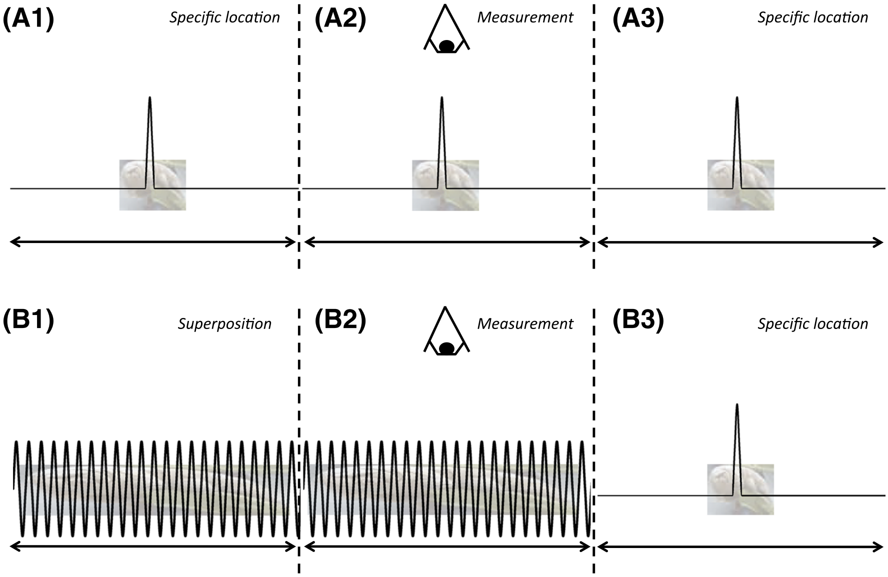

Fig. 1 A schematic illustration of the act of someone observing (*A1–3*) a normally occurring, decoherent tardigrade, as compared to (*B1–3*) a tardigrade that is in a coherent superposition of location states. *Solid black lines* represent the tardigrades wave function. (*A1*) Decoherent tardigrade in a specific location. (*A2*) Tardigrade is observed (measured). (*A3*) Tardigrade is now known to be in that location, but undergoes no physical change. (*B1*) Coherent tardigrade is in more than one location simultaneously, with a probability of being observed at each. (*B2*) Tardigrade is observed (measured). (*B3*) Act of observation causes the wave function to collapse, so that the tardigrade is now decoherent and known to be in one specific location. Tardigrade image modified from Eye of Science/Science Source Images

biologists interested in a full introduction to basic quantum mechanics, Davies and Betts (2002) is recommended.

In order to place an object into a coherent state in the laboratory, it is necessary to isolate it from interactions with its environment. Simplistically, this requires placing the object in a vacuum and cooling sufficiently so that its own internal thermal vibrations do not cause it to decohere. However, it should be noted that the role of interactions disrupting quantum effects is complex, and the fact there is some evidence that living organisms do internally make use of quantum phenomena would imply that quantum effects can occur within warm and non-isolated environments (Ball 2011; Bordonaro and Ogryzko 2013). For the present at least, a practical challenge to coercing objects into a coherent state is that they must be contained within a vacuum and sufficiently cooled—the former to prevent decoherence resulting from interactions with the external environment, the latter to prevent decoherence through thermal vibrational excitation of the object (or of components internal to the object). Such factors limit the size of object that can currently be placed in a quantum coherent state: the larger the object, the more difficult it is to cool and isolate the object sufficiently. A key quantum phenomenon—wave–particle duality—has long been demonstrable in buckminsterfullerenes (C-60), which have a diameter ~ 1 nm and are 'almost classical' in size (Arndt et al. 1999). As technology continues to improve, it has been possible for physicists to demonstrate coherence in larger and larger objects. More recently, it has been shown that *macroscopic* inanimate objects, on the scale of μm, can also be coerced into exhibiting coherent quantum behavior, specifically a superposition of motion states (O'Connell et al. 2010).

The proposed experiments

Romero-Isart et al. (2010) have proposed an experiment by which lasers would be used to cool (i.e. limit rotational and/or translational motion) and trap a virus, inside what is known as an optical cavity. The virus would be decoupled from its environment and thereby able to be coerced into a coherent quantum state. More specifically, the centre of mass of the virus would be in a superposition of motion states, meaning that the virus was effectively moving (within the confines of the trap) in a number of different ways *at the same time*. Romero-Isart et al. claim that this "opens up the possibility of testing the quantum nature of living organisms" (i.e. motion as whole quantum objects) such as the common Influenza and Tobacco Mosaic viruses, and potentially larger organisms such as tardigrades. It should be noted that, although the point is not acknowledged by Romero-Isart et al. (2010), there is no consensus amongst biologists as to whether viruses actually comprise living systems (Nasir et al. 2012). However, since the application of the experimental technique is also discussed in relation to tardigrades and other extremophiles, which certainly seem to meet the criteria of being "alive", we do not discuss the virus debate any further.

The proposed experiment would result in a living object that is in a superposition of states in relation to e.g. the motion of its centre of mass along one axis. An organism in such an experimental setup would then be subjected to a quantum state, where it would be in a number of different states of motion at the same time, constituting a classically impossible combination of movements. So for instance, unlike a decoherent virus with a certain translational motion and a specific location at a given point in time (Fig. 2a), the coherent virus might be undergoing a combination of translational motions, and thereby also be in an undetermined location in space (Fig. 2b, c).

Whether a tardigrade as an organism can be said to "experience" its own movement at all is another topic of discussion, and we do not explore that here. Further, the experimental technique proposed by Romero-Isart et al. has yet to be achieved in practice for objects large enough to comprise a living system, although progress continues to be made towards doing so for inanimate nanospheres

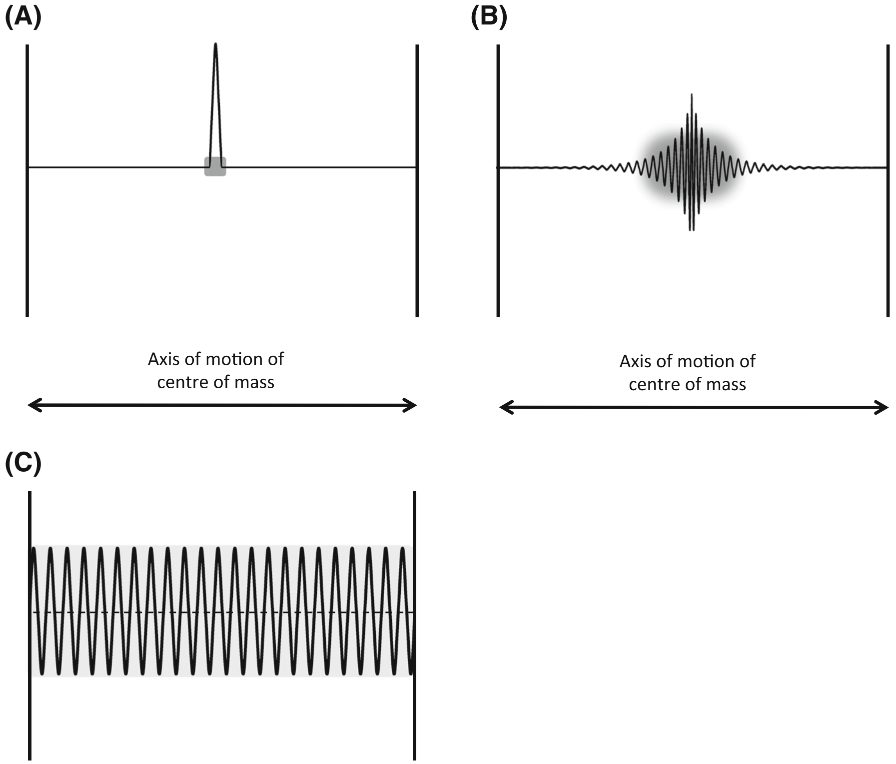

Fig. 2 Schematic illustrating how quantum phenomena might be exhibited if displayed by a virus (*grey rectangular shape*) in an experiment such as that described by Romero-Isart et al. (2010). **a** decoherent virus in a potential trap, with defined position and known movement along the axis of motion; **b** partially coherent virus in the same trap, movement along this axis is less certain. Possible location is consequently described by a wave function, which is given by the black oscillatory line (the location of the virus staying is the amplitude of the wave function at that point squared); **c** fully coherent virus in the same trap, state of motion along the axis is entirely uncertain until measured. Location is determined proportional to the wave function, which is given by the oscillatory black line. Note that this schematic is conceptually illustrative only i.e. the functional form of the wave function has not been derived

(e.g. Kiesel et al. 2013—who report trapping of submicron particles with a radius of ~169 nm), and once it is successfully achieved for larger nanospheres the experiment with viruses is likely to be carried out (O. Romero-Isart, pers. comm.). Nevertheless, the fundamental question that it should inspire for biologists remains worthy of consideration: can living organisms exhibit quantum mechanical properties as whole systems whilst remaining alive, or at least retain the potential to become alive again, and if so, what are the implications? To begin to answer this question, we must first consider some relevant biology—not least the current understanding of a 'living organism'.

Living organisms

A universal definition for what comprises 'living' has yet to be agreed (Schrödinger 1944; McKay 2004), but a common working definition is that an organism is a "self-sustaining chemical system capable of Darwinian evolution" (Benner 2010). Arguments have been made against this definition (e.g. Ruiz-Mirazo et al. 2004; Leitner and Firneis 2011) and others have made attempts to describe life in terms of more specific characteristics. A widely cited set of fundamental living characteristics can be summarized by the acronym PICERAS (Koshland 2002; Table 1): Program, Improvisation, Compartmentalization, Energy, Regeneration, Adaptability, and Seclusion. Whilst this has been recognized by many (including Koshland) not to represent either a true definition or even necessarily a definitive list of characteristics (e.g. Cleland and Chyba 2002), it usefully summarizes a common

Table 1 Characteristics of living systems, based upon Koshland's PICERAS model of the "pillars of life" (Koshland 2002)

Characteristic	Physical interpretation	Biological interpretation
Program	Set of instructions determining behaviour	Contained in RNA/DNA
Improvisation	Ability to modify program in response to environment	Evolution
Compartmentalization	Defined boundary, and isolation of subspaces within the main system, to separate processes	Cells as the fundamental unit of known life
Energy	Required for processes and to maintain low entropy	Living systems consume energy in low entropy forms
Regeneration	Compensate for thermodynamic losses, replace missing system components	Metabolism, replace damaged biological components
Adaptability	Ability to respond to environment without changing program	Behavioral change in response to external stimuli
Seclusion	Separation of chemical pathways	Biological molecules (e.g. enzymes) are disparately structured so that they provide specific functions only

perception of what a living thing is and does. Note that, because of the requirement to have the capacity to evolve ('improvise' according to Koshland), this set of characteristics applies to whole organisms but not to subcomponents of organisms (e.g. single cells that are not independent). The PICERAS set of characteristics is intended to apply to life at all spatial scales down to the smallest animate objects known to science, which are of the order 300–500 nm. This excludes certain nanobacteria ($\sim$50 nm) and viruses ($\sim$10–50 nm), which are again not widely accepted to be living organisms (US National Research Council 1999).

The fact that inanimate objects approaching the size of the smallest known living organisms can demonstrably be made coherent—and that certain organisms are known to be able to survive highly extreme conditions, as discussed below—means that it is perhaps inevitable that an experiment such as that proposed by Romero-Isart et al. will soon be carried out. As far as the authors are aware, this would represent an entirely new avenue of study in the field of quantum biology.

Quantum biology

Quantum biology is an emerging discipline, concerned with the extent to which quantum mechanical phenomena are important to, or even purposefully utilized by, living organisms (Ball 2011). There has for some time been speculation that living organisms internally make use of quantum phenomena (e.g. Penrose 1989; Hameroff 1994; Davies 2004). In order for this to occur, coherence would need to be sustained with the biochemical setting of the living system (Davies 2004) through a process such as 'internal error correction' (Igamberdiev 2004). Researchers have recently begun to show that this is possible (Gauger et al. 2011), and new research programmes are in progress to examine quantum phenomena at the molecular and cellular levels within biological systems (Bordonaro and Ogryzko 2013). Others have proposed the possibility of appropriating mathematical tools from quantum mechanics to model whole ecosystems (Bull 2015; Rodríguez et al. 2015). However, the Romero-Isart et al. experiment would, for the first time, examine actual quantum effects at the level of a whole organism. It is this latter point that we discuss here, which involves the potential implications of coercing a whole living organism (rather than components or sub-components of organisms, such as cells) into exhibiting quantum mechanical behaviour. This topic is important not only to biologists in understanding how living systems function, but also for physicists seeking a better understanding of how to maintain coherence in complex systems (Ball 2011), and of the so-called 'quantum to classical transition' (Bordonaro and Ogryzko 2013).

Whilst living organisms are increasingly thought to utilize quantum phenomena, or even to rely upon them by maintaining a level of coherence within subcomponents where necessary, organisms as a whole have only ever been known to behave as classical objects (Davies 2004; Ball 2011). That is, whole living organisms have to date never physically been shown to exhibit quantum effects such as e.g. wave–particle duality in a double slit experiment (although this experiment has been carried out on organic molecules; Becker 2011; Gerlich et al. 2011). By way of explanation: a common version of the double slit experiment finds that, when a coherent electron is fired through a barrier with two adjacent slits, and a detector is later used to monitor which slit the electron passed through, the electron will be recorded by the detector as a discrete ‘particle’. However, after many electrons have been fired through the slits, a more general interference pattern will build up on the detector, consistent with a mathematical description of the electron wave functions as having travelled through both slits simultaneously and interfered with themselves (i.e. the electron also acts as a ‘wave’).

Many physicists, to paraphrase the renowned Anton Zeilinger, would consider the coercion of animate (as opposed to inanimate) objects into a coherent state to be just a question of money and technological innovations—implying it may be of limited interest (Arndt et al. 2005). To biologists, however, there may be more important ramifications of creating living organisms in coherent quantum states. One example, which we discuss here, would be the relevance for the study of cryptobiology.

Cryptobiology

Cryptobiosis (i.e. hidden life) is a state that certain organisms are known to spend time in, and can be defined as “the state of an organism when it shows no visible signs of life and when its metabolic activity becomes hardly measurable, or comes reversibly to a standstill” (Keilin 1959; Clegg 2001). A key word in this definition is “reversibly”: cryptobiosis requires that the organism can return to a non-cryptic, living state after being, for instance, frozen—rather than expiring. There are five known drivers for a suitably equipped organism to assume a cryptobiotic state: anhydrobiosis (i.e. extreme dessication), anoxybiosis (i.e. in response to a lack of oxygen), chemobiosis (i.e. a response to very high levels of toxins in the environment), cryobiosis (i.e. at very low temperatures), and osmobiosis (i.e. a response to increased levels of solute) (Crowe 1975). Now, in order to place an organism into a coherent state using a methodology such as that described by Romero-Isart et al., as discussed, it may first have to be placed in a vacuum and cooled to low temperatures to prevent loss of coherence. The result would be that, in the case of this specific experiment, the organism might assume an anoxybiotic or cryobiotic state (respectively) as a precursor to entering the coherent state.

The interesting question from a biological perspective is, then, having potentially already placed the organism into an anoxybiotic or cryobiotic state, does coercing it into a quantum coherent state imply a different category of cryptobiosis? As discussed above, a necessary condition for an organism to remain in a coherent state would be for it to remain isolated from its environment, implying that no measurements could be taken of it. Therefore, it would not be able to have any *measurable* metabolic activity while in a coherent state (noting that metabolic rate is the rate at which an organism expends energy, which biologists measure in practice through proxies such as rate of gas exchange). The fact that the organism was in a coherent state could be demonstrated without direct interaction or measurement via detection of quantum effects, similarly to the presence of interference patterns found in electrons exposed to the aforementioned double slit experiment.

Thus, it would have to be concluded that an organism in a coherent state is indeed in a state of cryptobiosis. But this state sets it apart from the other five known classes of cryptobiosis: all of which are states in which metabolic activity can be searched for (e.g. it can be estimated to what degree an organism has managed to expend energy, for instance by assessing how much oxygen it has consumed), but just not physically detected. In a coherent state, metabolic activity cannot be detected—because it is, in principle, impossible to take a measurement without altering the state. A biologist might argue that this conclusion is a question of semantics, but this is because biology tends to treat the act of measurement as something neutral, rather than as an action that physically alters the system being measured (c.f. Fig. 1). Consequently, upon closer inspection, this conclusion may be more profound.

Although they do not outline it explicitly, Romero-Isart et al. seem to imply that the experiment could be considered successful if the organism were coerced into being coherent, and then survived the collapse back into a decoherent state. If this is achieved, then the biologist has to conclude that an organism in a coherent state is cryptobiotic—but in a new way compared to previously observed classes of cryptobiosis. This is not the only potentially interesting outcome of the experiment from a biological point of view. In addition, the outcomes have relevance for a PICERAS-type understanding of living things.

Compartmentalization

The validity of the PICERAS set of characteristics has not, to our knowledge, been fully explored for organisms in a cryptobiotic state. But consider, for instance, an organism that is frozen and hence demonstrates no metabolic activity (i.e. is in a cryobiotic state)—then so long as it may return to an active living state upon warming, it would still exhibit the full set of PICERAS set of characteristics (Table 1). It clearly continues to have a Program, is Compartmentalized, and contains Secluded molecules. It cannot demonstrate Improvisation, Regeneration or Adaptability whilst remaining in the cryptobiotic state, but has the capacity to exhibit all three of these characteristics if warmed. Thus a frozen organism has the *potential* for Improvisation, Regeneration or Adaptability. Similarly, it would require Energy in order to maintain low entropy levels, if it were to return to being a dynamic system or change state in any way, arguably satisfying the last of the 7 PICERAS categories.

Almost exactly the same reasoning applies to an organism that is in a coherent quantum state, in the manner proposed by Romero-Isart et al. An organism in a superposition of motion states would similarly still have a Program. Further, it would most certainly have the potential for Improvisation, Regeneration and Adaptability if it could survive returning to a decoherent state. It would retain a latent need for Energy and Seclusion once it lapsed back into decoherence. However, it is possible that whilst the potential for Compartmentalization might be maintained, this characteristic could actually be compromised in such a state. To explain: living systems have a definite boundary, and are also comprised of numerous sub-hierarchical components that themselves have defined boundaries. All known living systems are composed of cells, but these cells might be grouped into organs, and contain organelles. These boundaries are crucial in that they allow matter to traverse them when it is useful to the organism, and also serve to both to keep out undesirable matter and to maintain important chemical processes in isolation (Koshland 2002). If an entire living system were in a coherent state, it would have no definite internal or external physical boundaries in space. Even if it retained its basic internal structure, in a superposition of motion states, the outer boundary would not be defined in a classical sense. Consequently, normally compartmentalized subcomponents of the organism could in a real sense be considered to be overlapping or non-localised in space, meaning that the characteristic of Compartmentalization had been violated.

Again, whilst such an event is perfectly acceptable from the point of view of an inanimate object, it would be a strange state of affairs for a living organism. Whether it is possible for an organism to experience this situation and remain living is, again, one outcome of the experiment that would be worth exploring further. At the very least, a more finessed interpretation of the characteristic of Compartmentalization would be required.

Implications

Here, we have considered certain biological implications of an experimental set up designed by physicists, which would place an organism into a coherent quantum state. The points that arise from a biologist's consideration of the Romero-Isart et al. experiment depend to an extent upon the outcomes. Firstly, if it is successful (i.e. coherence is achieved and the organism remains alive after returning to a decoherent state), then an organism will have been temporarily in a state where it has an unmeasurable metabolism: not because a metabolic rate is undetectable, but because any attempt to measure it would automatically bring the organism out of the state. This is in essence a new category of cryptobiosis which to date has been unobserved. Aside from intellectual curiosity, this would be of interest to science and to biologists in particular: because it would extend current understanding of the extreme conditions under which life can persist, and because it would open up a new avenue for exploration in the field of quantum biology.

Secondly, it is not abundantly clear whether the organism could be considered to have demonstrated only partial Compartmentalization, in the sense meant by a biologist, whilst in the coherent state. This would be an interesting avenue for further research, as it would bring into question the validity of characteristics often associated with living things, particularly the assumption that a cellular structure represents a fundamental requirement (Table 1). Whilst it is already accepted by many that we do not have a satisfactory set of characteristics that define an animate organism (Koshland 2002), such a finding would further shape the debate.

More generally, if it is shown that living organisms can survive being in a coherent state, then we must accept that life does not necessarily require living things to be decoherent—which is in itself a fundamental consideration for biologists, even if it may seem trivial to a physicist. The idea that living things could occupy coherent states would be new to biology, and would perhaps even eventually extend the scope of what is considered possible biologically. By way of just one example that highlights the implications, the field of astrobiology is in part the search for extra-terrestrial life (Morrison 2001), and a key challenge in that search lies in knowing what exactly to look for (McKay 2004). Whilst many argue that terrestrial life offers a good template for life elsewhere in the universe (Lineweaver and Chopra 2011), it is readily accepted by others that living systems might exhibit entirely different biochemistry to life on earth (McKay 2011). Given that the definition of life guides the search for it in exotic places, the results of experiments such as the one suggested by Romero-Isart et al. (2010) could influence the exploration for life elsewhere in the solar system.

Finally, and perhaps most intriguing of all, would be if it proved impossible for an organism to resume metabolic activity after being in a coherent state, i.e. if the act of becoming coherent in the proposed experiment always killed it. There is no reason why this should be so from a physical perspective, as far as we know. But it would seem that the two statements:

1. Every object or system in the universe, in principle, can be described by a quantum wave function that is coherent or decoherent to some degree; and,
2. Every living organism that is placed into a coherent state dies,

are incompatible. Statement (1) relates to a mainstream interpretation of quantum theory, statement (2) is a potential outcome of the Romero-Isart et al. experiment. If (2) is shown to be true, that would not suggest that quantum theory is misguided—rather, that the current physical understanding of the universe does not adequately capture animation as a characteristic. That is to say, if it proved to be the case, then it would provide some evidence that living systems have properties that do not fit within our current physical understanding of the universe.

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References

Arndt M, Nairz O, Vos-Andreae J, Keller C, van der Zouw G, Zeilinger A (1999) Wave–particle duality of C_{60} molecules. Nature 401:680–682

Arndt M, Aspelmeyer M, Bernstein HJ, Bertlmann R, Brukner C, et al (2005) Quantum physics from A to Z. arXiv:quant-ph/0505187

Ball P (2011) Physics of life: the dawn of quantum biology. Nature 474:272–274

Becker U (2011) Molecular physics: matter-wave interference made clear. Nature 474:586–587

Benner SA (2010) Defining life. Astrobiology 10(10):1021–1030

Bordonaro M, Ogryzko V (2013) Quantum biology at the cellular level—elements of the research programme. BioSystems 112(1):11–30

Bull JW (2015) Quantum conservation biology, a new ecological tool. Conser Lett. doi:10.1111/conl.12195

Clegg JS (2001) Cryptobiosis—a peculiar state of biological organization. Comp Biochem Physiol Part B 128:613–624

Cleland CE, Chyba CF (2002) Defining 'life'. Origins Life Evol Biosphere 32:387–393

Crowe JH (1975) The physiology of cryptobiosis in tardigrades. Mem Its Ital Idrobiol 32:37–59

Davies PCW (2004) Does quantum mechanics play a non-trivial role in life? BioSystems 78:69–79

Davies PCW, Betts DS (2002) Quantum mechanics, 2nd edn. Nelson Thornes, Cheltenham

Gauger EM, Rieper E, Morton JJL, Benjamin SC, Vedral V (2011) Sustained quantum coherence and entanglement in the avian compass. Phys Rev Lett 106:040503

Gerlich G, Eibenberger S, Tomandl M, Nimmrichter S, Hornberger K et al (2011) Quantum interference of large organic molecules. Nat Commun. doi:10.1038/ncomms1263

Hameroff SR (1994) Quantum coherence in microtubules: a neural basis for emergent consciousness? J Conscious Stud 1:98–118

Igamberdiev AU (2004) Quantum computation, non-demolition measurements, and reflective control in living systems. BioSystems 77(1–3):47–56

Keilin D (1959) The problem of anabiosis or latent life: history and current concept. Proc R Soc Lond B 150:149–191

Kiesel N, Blaser F, Delic U, Grass D, Kaltenbaek R, Aspelmeyer M (2013) Cavity cooling of an optically levitated submicron particle. PNAS 110(35):14180–14185

Koshland DE (2002) The seven pillars of life. Science 295:2215–2216

Leitner JJ, Firneis MG (2011) Defining life in a non-geocentric way. EPSC abstracts, EPSC-DPS joint meeting 2011: vol 6, EPSC-DPS2011-1114

Lineweaver CH, Chopra A (2011) What can life on earth tell us about life in the universe? In: Seckbach J (ed) Genesis—in the beginning: precursors of life, chemical models and early biological evolution, cellular origin, life in extreme habitats and astrobiology. Springer, New York, pp 799–815

McKay CP (2004) What is life—and how do we search for it in other worlds? PLoS Biol 2(9):1260–1263

McKay CP (2011) The search for life in our solar system and the implications for science and society. Philos Trans R Soc A 369:594–606

Morrison D (2001) The NASA astrobiology program. Astrobiology 1(1):3–13

Nasir A, Kim KM, Caetano-Anolles G (2012) Giant viruses coexisted with the cellular ancestors and represent a distinct supergroup along with superkingdoms Archaea, Bacteria and Eukarya. BMC Evol Biol 12:156

O'Connell AD, Hofheinz M, Ansmann M, Bialczak RC, Lenander M, Lucero E, Neeley M, Sank D, Wang H, Weides M, Wenner J, Martinis JM, Cleland AN (2010) Quantum ground state and single-phonon control of a mechanical resonator. Nature 464:697–703

Penrose R (1989) The Emperor's new mind. Oxford University Press, Oxford

Rodríguez RA, Herrera AM, Riera R, Escudero CG, Delgado JD (2015) Empirical clues about the fulfillment of quantum principles in ecology: potential meaning and theoretical challenges. Ecol Model 301:90–97

Romero-Isart O, Juan ML, Quidant R, Cirac JI (2010) Toward quantum superposition of living organisms. New J Phys 12(3):033015

Ruiz-Mirazo K, Peretó J, Moreno A (2004) A universal definition of life: autonomy and open-ended evolution. Origins Life Evol Biospheres 34(3):323–346

Schrödinger E (1944) What is life? The physical aspect of the living cell. Cambridge University Press, Cambridge

US National Research Council (1999) Size limits of very small microorganisms: proceedings of a workshop. National Academies Press, Washington, DC

Zurek WH (1991) Decoherence and the transition from quantum to classical. Phys Today 44(10):36

Zurek WH (2003) Decoherence and the transition from quantum to classical—revisited (preprint). arXiv:quant-ph/0306072