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

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27

28

29 **Abstract**

30 Consideration of the experimental activities carried out in one discipline, through the lens of
31 another, can lead to novel insights. Here, we comment from a biological perspective upon
32 experiments in quantum mechanics proposed by physicists that are likely to be feasible in the
33 near future. In these experiments, an entire living organism would be knowingly placed into a
34 coherent quantum state for the first time, i.e. would be coerced into demonstrating quantum
35 phenomena.

36

37 The implications of the proposed experiment for a biologist depend to an extent upon the
38 outcomes. If successful (i.e. quantum coherence is achieved and the organism survives after
39 returning to a normal state), then the organism will have been temporarily in a state where it
40 has an unmeasurable metabolism – not because a metabolic rate is undetectable, but
41 because any attempt to measure it would automatically bring the organism out of the state.
42 We argue that this would in essence represent a new category of cryptobiosis. Further, the
43 organism would not necessarily retain all of the characteristics commonly attributed to living
44 systems, unlike the currently known categories of cryptobiosis.

45

46 If organisms can survive having previously been in a coherent state, then we must accept that
47 living systems do not necessarily need to remain in a decoherent state at all times. This would
48 be something new to biologists, even if it might seem trivial to physicists. It would have
49 implications concerning the physical extremes organisms can tolerate, the search for
50 extraterrestrial life, and our philosophical view of animation.

51

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

64

65 *Quantum theory and the concept of decoherence*

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

88

89 As a hypothetical example, imagine a tardigrade that was at an unknown location: if the
90 tardigrade was in a decoherent state, then an observer could locate it by attempting to
91 measure its position. Subsequently, the observer could legitimately describe the tardigrade as

92 having had a defined position in space immediately prior to measurement. But if it were in a
93 coherent quantum state, this would mean it was in a “superposition of states”, or, spread out
94 over numerous locations at the same time, with a probability of being found at each. The act
95 of observing the coherent tardigrade (i.e. interacting with it) would have caused its wave
96 function to collapse, with the result that it would decohere and subsequently become localized
97 to a specific point in space (Fig. 1).

98
99 In systems we perceive as exhibiting classical behavior, such as most macroscopic systems,
100 the majority of the quantum information about the system is already lost as a result of
101 interactions with the environment (“measurement” being just one form of interaction with the
102 environment). That is to say, the wave function describing such systems is constantly being
103 collapsed into a single decoherent state as a result of these interactions (Zurek, 1991). A
104 decoherent system is indistinguishable from a system behaving deterministically, as
105 described by classical mechanics, which is why macroscopic systems built from components
106 small enough to experience quantum effects don’t exhibit this behaviour. For biologists
107 interested in a full introduction to basic quantum mechanics, Davies & Betts (2002) is
108 recommended.

109
110 In order to place an object into a coherent state in the laboratory, it is necessary to isolate it
111 from interactions with its environment. Simplistically, this requires placing the object in a
112 vacuum and cooling sufficiently so that its own internal thermal vibrations do not cause it to
113 decohere. However, it should be noted that the role of interactions disrupting quantum effects
114 is complex, and the fact there is some evidence that living organisms do internally make use
115 of quantum phenomena would imply that quantum effects can occur within warm and non-
116 isolated environments (Ball, 2011; Bordonaro & Ogryzko, 2013). For the present at least, a
117 practical challenge to coercing objects into a coherent state is that they must be contained
118 within a vacuum and sufficiently cooled – the former to prevent decoherence resulting from
119 interactions with the external environment, the latter to prevent decoherence through thermal
120 vibrational excitation of the object (or of components internal to the object). Such factors limit
121 the size of object that can currently be placed in a quantum coherent state: the larger the
122 object, the more difficult it is to cool and isolate the object sufficiently. A key quantum
123 phenomenon – wave-particle duality – has long been demonstrable in buckminsterfullerenes
124 (C-60), which have a diameter ~ 1 nm and are ‘almost classical’ in size (Arndt et al., 1999).
125 As technology continues to improve, it has been possible for physicists to demonstrate
126 coherence in larger and larger objects. More recently, it has been shown that *macroscopic*
127 inanimate objects, on the scale of μm , can also be coerced into exhibiting coherent quantum
128 behavior, specifically a superposition of motion states (O’Connell et al., 2010).

129

130 *The proposed experiments*

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

145
146 The proposed experiment would result in a living object that is in a superposition of states in
147 relation to e.g. the motion of its centre of mass along one axis. An organism in such an
148 experimental setup would then be subjected to a quantum state, where it would be in a
149 number of different states of motion at the same time, constituting a classically impossible
150 combination of movements. So for instance, unlike a decoherent virus with a certain
151 translational motion and a specific location at a given point in time (Fig. 2A), the coherent
152 virus might be undergoing a combination of translational motions, and thereby also be in an
153 undetermined location in space (Fig. 2B,C).

154
155 Whether a tardigrade as an organism can be said to “experience” its own movement at all is
156 another topic of discussion, and we do not explore that here. Further, the experimental
157 technique proposed by Romero-Isart et al. has yet to be achieved in practice for objects large
158 enough to comprise a living system, although progress continues to be made towards doing
159 so for inanimate nanospheres (e.g. Kiesel et al., 2013 – who report trapping of submicron
160 particles with a radius of ~ 169 nm), and once it is successfully achieved for larger
161 nanospheres the experiment with viruses is likely to be carried out (O. Romero-Isart, pers.
162 comm.). Nevertheless, the fundamental question that it should inspire for biologists remains
163 worthy of consideration: can living organisms exhibit quantum mechanical properties as whole
164 systems whilst remaining alive, or at least retain the potential to become alive again, and if so,
165 what are the implications? To begin to answer this question, we must first consider some
166 relevant biology – not least the current understanding of a ‘living organism’.

167

168 *Living organisms*

169 A universal definition for what comprises 'living' has yet to be agreed (McKay, 2004), but a
170 common working definition is that an organism is a "self-sustaining chemical system capable
171 of Darwinian evolution" (Benner, 2010). Arguments have been made against this definition
172 (e.g. Ruiz-Mirazo et al., 2004; Leitner & Firneis, 2011) and others have made attempts to
173 describe life in terms of more specific characteristics. A widely cited set of fundamental living
174 characteristics can be summarized by the acronym PICERAS (Koshland, 2002; Table 1):
175 Program, Improvisation, Compartmentalization, Energy, Regeneration, Adaptability, and
176 Seclusion. Whilst this has been recognized by many (including Koshland) not to represent
177 either a true definition or even necessarily a definitive list of characteristics (e.g. Cleland &
178 Chyba, 2002), it usefully summarizes a common perception of what a living thing is and does.
179 Note that, because of the requirement to have the capacity to evolve ('improvise' according to
180 Koshland), this set of characteristics applies to whole organisms but not to subcomponents of
181 organisms (e.g. single cells that are not independent). The PICERAS set of characteristics is
182 intended to apply to life at all spatial scales down to the smallest animate objects known to
183 science, which are of the order 300 – 500 nm. This excludes certain nanobacteria (~ 50 nm)
184 and viruses (~ 10 – 50 nm), which are again not widely accepted to be living organisms (US
185 National Research Council, 1999).

186

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

193

194 *Quantum biology*

195 Quantum biology is an emerging discipline, concerned with the extent to which quantum
196 mechanical phenomena are important to, or even purposefully utilized by, living organisms
197 (Ball, 2011). There has for some time been speculation that living organisms internally make
198 use of quantum phenomena (e.g. Penrose, 1989; Hameroff, 1994; Davies, 2004). In order for
199 this to occur, coherence would need to be sustained with the biochemical setting of the living
200 system (Davies, 2004) through a process such as 'internal error correction' (Igamberdiev,
201 2004). Researchers have recently begun to show that this is possible (Gauger et al., 2011),
202 and new research programmes are in progress to examine quantum phenomena at the
203 molecular and cellular levels within biological systems (Bordonaro & Ogryzko, 2013). Others
204 have proposed the possibility of appropriating mathematical tools from quantum mechanics to
205 model whole ecosystems (Bull, 2015; Rodríguez et al., 2015). However, the Romero-Isart et
206 al. experiment would, for the first time, examine actual quantum effects at the level of a whole
207 organism. It is this latter point that we discuss here, which involves the potential implications

208 of coercing a whole living organism (rather than components or sub-components of
209 organisms, such as cells) into exhibiting quantum mechanical behaviour. This topic is
210 important not only to biologists in understanding how living systems function, but also for
211 physicists seeking a better understanding of how to maintain coherence in complex systems
212 (Ball, 2011), and of the so-called ‘quantum to classical transition’ (Bordonaro & Ogryzko,
213 2013).

214
215 Whilst living organisms are increasingly thought to utilize quantum phenomena, or even to
216 rely upon them by maintaining a level of coherence within subcomponents where necessary,
217 organisms as a whole have only ever been known to behave as classical objects (Davies,
218 2004; Ball, 2011). That is, whole living organisms have to date never physically been shown
219 to exhibit quantum effects such as e.g. wave-particle duality in a double slit experiment
220 (although this experiment has been carried out on organic molecules; Becker, 2011; Gerlich
221 et al., 2011). By way of explanation: a common version of the double slit experiment finds that,
222 when a coherent electron is fired through a barrier with two adjacent slits, and a detector is
223 later used to monitor which slit the electron passed through, the electron will be recorded by
224 the detector as a discrete ‘particle’. However, after many electrons have been fired through
225 the slits, a more general interference pattern will build up on the detector, consistent with a
226 mathematical description of the electron wave functions as having travelled through both slits
227 simultaneously and interfered with themselves (i.e. the electron also acts as a ‘wave’).

228
229 Many physicists, to paraphrase the renowned Anton Zeilinger, would consider the coercion of
230 animate (as opposed to inanimate) objects into a coherent state to be just a question of
231 money and technological innovations – implying it may be of limited interest (Arndt et al.,
232 2005). To biologists, however, there may be more important ramifications of creating living
233 organisms in coherent quantum states. One example, which we discuss here, would be the
234 relevance for the study of cryptobiology.

235

236 *Cryptobiology*

237 Cryptobiosis (i.e. hidden life) is a state that certain organisms are known to spend time in, and
238 can be defined as “the state of an organism when it shows no visible signs of life and when its
239 metabolic activity becomes hardly measurable, or comes reversibly to a standstill” (Keilin,
240 1959; Clegg, 2001). A key word in this definition is “reversibly”: cryptobiosis requires that the
241 organism can return to a non-cryptic, living state after being, for instance, frozen – rather than
242 expiring. There are five known drivers for a suitably equipped organism to assume a
243 cryptobiotic state: anhydrobiosis (i.e. extreme dessication), anoxybiosis (i.e. in response to a
244 lack of oxygen), chemobiosis (i.e. a response to very high levels of toxins in the environment),
245 cryobiosis (i.e. at very low temperatures), and osmobiosis (i.e. a response to increased levels
246 of solute) (Crowe, 1975). Now, in order to place an organism into a coherent state using a
247 methodology such as that described by Romero-Isart et al., as discussed, it may first have to

248 be placed in a vacuum and cooled to low temperatures to prevent loss of coherence. The
249 result would be that, in the case of this specific experiment, the organism might assume an
250 anoxybiotic or cryobiotic state (respectively) as a precursor to entering the coherent state.

251
252 The interesting question from a biological perspective is, then, having potentially already
253 placed the organism into an anoxybiotic or cryobiotic state, does coercing it into a quantum
254 coherent state imply a different category of cryptobiosis? As discussed above, a necessary
255 condition for an organism to remain in a coherent state would be for it to remain isolated from
256 its environment, implying that no measurements could be taken of it. Therefore, it would not
257 be able to have any *measurable* metabolic activity while in a coherent state (noting that
258 metabolic rate is the rate at which an organism expends energy, which biologists measure in
259 practice through proxies such as rate of gas exchange). The fact that the organism was in a
260 coherent state could be demonstrated without direct interaction or measurement via detection
261 of quantum effects, similarly to the presence of interference patterns found in electrons
262 exposed to the aforementioned double slit experiment.

263
264 Thus, it would have to be concluded that an organism in a coherent state is indeed in a state
265 of cryptobiosis. But this state sets it apart from the other five known classes of cryptobiosis: all
266 of which are states in which metabolic activity can be searched for (e.g. it can be estimated to
267 what degree an organism has managed to expend energy, for instance by assessing how
268 much oxygen it has consumed), but just not physically detected. In a coherent state,
269 metabolic activity cannot be detected – because it is, in principle, impossible to take a
270 measurement without altering the state. A biologist might argue that this conclusion is a
271 question of semantics, but this is because biology tends to treat the act of measurement as
272 something neutral, rather than as an action that physically alters the system being measured
273 (c.f. Fig. 1). Consequently, upon closer inspection, this conclusion may be more profound.

274
275 Although they do not outline it explicitly, Romero-Isart et al. seem to imply that the experiment
276 could be considered successful if the organism were coerced into being coherent, and then
277 survived the collapse back into a decoherent state. If this is achieved, then the biologist has to
278 conclude that an organism in a coherent state is cryptobiotic – but in a new way compared to
279 previously observed classes of cryptobiosis. This is not the only potentially interesting
280 outcome of the experiment from a biological point of view. In addition, the outcomes have
281 relevance for a PICERAS-type understanding of living things.

282

283 *Compartmentalization*

284 The validity of the PICERAS set of characteristics has not, to our knowledge, been fully
285 explored for organisms in a cryptobiotic state. But consider, for instance, an organism that is
286 frozen and hence demonstrates no metabolic activity (i.e. is in a cryobiotic state) – then so
287 long as it may return to an active living state upon warming, it would still exhibit the full set of

288 PICERAS set of characteristics (Table 1). It clearly continues to have a Program, is
289 Compartmentalized, and contains Secluded molecules. It cannot demonstrate Improvisation,
290 Regeneration or Adaptability whilst remaining in the cryptobiotic state, but has the capacity to
291 exhibit all three of these characteristics if warmed. Thus a frozen organism has the *potential*
292 for Improvisation, Regeneration or Adaptability. Similarly, it would require Energy in order to
293 maintain low entropy levels, if it were to return to being a dynamic system or change state in
294 any way, arguably satisfying the last of the 7 PICERAS categories.

295

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

315

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

321

322 *Implications*

323 Here, we have considered certain biological implications of an experimental set up designed
324 by physicists, which would place an organism into a coherent quantum state. The points that
325 arise from a biologist's consideration of the Romero-Isart et al. experiment depend to an
326 extent upon the outcomes. Firstly, if it is successful (i.e. coherence is achieved and the
327 organism remains alive after returning to a decoherent state), then an organism will have

328 been temporarily in a state where it has an unmeasurable metabolism: not because a
329 metabolic rate is undetectable, but because any attempt to measure it would automatically
330 bring the organism out of the state. This is in essence a new category of cryptobiosis which to
331 date has been unobserved. Aside from intellectual curiosity, this would be of interest to
332 science and to biologists in particular: because it would extend current understanding of the
333 extreme conditions under which life can persist, and because it would open up a new avenue
334 for exploration in the field of quantum biology.

335

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

343

344 More generally, if it is shown that living organisms can survive being in a coherent state, then
345 we must accept that life does not necessarily require living things to be decoherent – which is
346 in itself a fundamental consideration for biologists, even if it may seem trivial to a physicist.

347 The idea that living things could occupy coherent states would be new to biology, and would
348 perhaps even eventually extend the scope of what is considered possible biologically. By way
349 of just one example that highlights the implications, the field of astrobiology is in part the
350 search for extra-terrestrial life (Morrison, 2001), and a key challenge in that search lies in
351 knowing what exactly to look for (McKay, 2004). Whilst many argue that terrestrial life offers a
352 good template for life elsewhere in the universe (Lineweaver & Chopra, 2011), it is readily
353 accepted by others that living systems might exhibit entirely different biochemistry to life on
354 earth (McKay, 2011). Given that the definition of life guides the search for it in exotic places,
355 the results of experiments such as the one suggested by Romero-Isart et al. (2010) could
356 influence the exploration for life elsewhere in the solar system.

357

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

362 (1) every object or system in the universe, in principle, can be described by a
363 quantum wave function that is coherent or decoherent to some degree; and,

364 (2) every living organism that is placed into a coherent state dies,

365 are incompatible. Statement (1) relates to a mainstream interpretation of quantum theory,
366 statement (2) is a potential outcome of the Romero-Isart et al. experiment. If (2) is shown to
367 be true, that would not suggest that quantum theory is misguided – rather, that the current

368 physical understanding of the universe does not adequately capture animation as a
369 characteristic. That is to say, if it proved to be the case, then it would provide some evidence
370 that living systems have properties that do not fit within our current physical understanding of
371 the universe.

372

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508 **Table 1: Characteristics of living systems, based upon Koshland's PICERAS model of the**
 509 **"pillars of life" (Koshland, 2002)**
 510

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

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

523

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

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