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PLENARY DEBATE: QUANTUM EFFECTS IN BIOLOGY: TRIVIAL OR NOT?

DEREK ABBOTT
Centre for Biomedical Engineering (CBME) and Department of Electrical & Electronic Engineering, The University of Adelaide, SA 5005, Australia

JULIO GEA-BANACLOCHE
Department of Physics, University of Arkansas, Fayetteville, AR 72701, USA

PAUL C. W. DAVIES
Beyond: Center for Fundamental Concepts in Science, Arizona State University P.O. Box 876505, Tempe, AZ 85287-6505, USA

STUART HAMEROFF
Department of Anesthesiology and Psychology, Center for Consciousness Studies University of Arizona, Tucson, AZ 85721, USA

ANTON ZEILINGER
Institut fr Experimentalphysik, Universität Innsbruck Technikerstrasse 25, 6020 Innsbruck, Austria

JENS EISERT
QOLS, Blackett Laboratory, Imperial College London, Prince Consort Road London SW7 2BW, United Kingdom and Institute for Mathematical Sciences, Imperial College London Prince's Gate, London SW7 2PE, United Kingdom

HOWARD WISEMAN
Centre for Quantum Computer Technology, Centre for Quantum Dynamics, Griffith University Brisbane, Qld. 4111, Australia

SERGEY M. BEZRUKOV
Laboratory of Physical and Structural Biology, NICHD, National Institutes of Health Bethesda, MD 20892-0924, USA

HANS FRAUENFELDER
Theory Division T10, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

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The Panel - Dramatis Personae

Chair/Moderator: **Julio Gea-Banacloche**, Univ. of Arkansas (USA); Editor of *Physical Review A*.

No Team (*assertion "not trivial"*):
Paul C. W. Davies, Macquarie University (Australia);
Stuart Hameroff, Univ. of Arizona (USA);
Anton Zeilinger, Univ. of Vienna (Austria);
Derek Abbott, Univ. of Adelaide (Australia); Editor of *Fluctuation Noise Lett.* and *Smart Structures and Materials*.

Yes Team (*assertion "trivial"*):
Jens Eisert, Imperial College (UK) and Potsdam University (Germany);
Howard Wiseman, Griffith University (Australia);
Sergey Bezrukov, National Institutes of Health (USA); Editor of *Fluctuation Noise Lett.*;
Hans Frauenfelder, Los Alamos National Laboratories (USA).

Transcript Editor:
Derek Abbott, The University of Adelaide (Australia);

Disclaimer: The views expressed by all the participants were for the purpose of lively debate and do not necessarily express their actual views.

Transcript conventions: Square brackets [...] containing a short phrase indicate that these words were not actually spoken, but were editorial insertions for clarity. Square brackets [...] containing a long section indicate that the recording was unclear and the speaker has tried to faithfully reconstruct what was actually said. [*sic*] indicates the transcript has been faithful to what was spoken, even though grammatically incorrect. Where acoustic emphasis was deemed to occur in the recording, the transcript reflects this with italics.

The Debate

Julio Gea-Banacloche (Chair): [I am pleased to introduce] this special debate, *Quantum effects in biology: trivial or not?* I am Julio Gea-Banacloche, originally from here: a native of Spain. As Laszlo Kish pointed out yesterday at the banquet that there was an intense pre-debate debate concerning what the debate should be about—and such topics as whether the title of the debate should phrased as a 'yes' or 'no' question or not. That's something some people were very adamant about and in some sense it is kind of a miracle that we are having this debate at all. I am

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really glad about it. So the question is: "Quantum effects in biology: trivial or not?" and on the Yes Team we have Professor Paul Davies from Macquarie University...

Stuart Hameroff (No Team): [Interrupts] We're the non-trivial team... we're the No Team!

Audience laughter

Julio Gea-Banacloche (Chair): See: sorry, I got it wrong already. With apologies to the teams, so, actually the No Team are the good guys, eh...

Audience laughter

Julio Gea-Banacloche (Chair): We must not get this bit confused. The No Team claim that quantum effects in biology are *not* trivial and we have Professor Paul Davies from Macquarie University, and Professor Stuart Hameroff from the University of Arizona, and Professor Anton Zeilinger, who is currently in a superposition of states and thus invisible[1]...

Audience laughter

Julio Gea-Banacloche (Chair): And masquerading as Jack Tuszynski is Professor Derek Abbott,[2] our organizer from The University of Adelaide. On the Yes Team we have Professor Jens Eisert, from the University of Potsdam; Professor Howard Wiseman, from Griffith University; Dr Sergey Bezrukov, from the National Institutes of Health; and Dr Hans Frauenfelder from Los Alamos National Labs. There are a couple of things about the way I see this today, and of course the audience—and they represent themselves—are welcome to think any way they want to. But way, way back in the early, early stages of the pre-debate debate, somebody had suggested the title of *Quantum mechanical effects on the mind: important or not?* I actually thought that was a very exciting question, not having any idea about what the possible answers might have been and what anybody might have to say for or against it. So at the time, when I was asked whether I would chair the debate, I thought that I would ask the panelists about their quantum mechanical states of mind and, if so, what drugs we need to take in order to experience them...

Audience laughter

Julio Gea-Banacloche (Chair): I would still like somebody to address that, except for the drugs part—which of course is just a joke. The other thing—that I am probably responsible for—is the final wording of the question: putting the word "trivial" in there. What I am personally expecting to get from this [is for] the No Team to try to provide some surprising facts—things that we would not have expected. In a sense, of course, we believe the entire world is described by quantum mechanics, so you can always say quantum mechanics is responsible for this or that. So what? Of course it would be responsible, because ultimately everything can be described by quantum mechanics. What I would like to see [are things that make me say] "I would not have expected that. Wow, this is unexpected. That is a surprise." That's the sort of thing that I would like to see come out of this. That is the sort of thing that would lead me to vote, if I were to vote, for the No Team

[1] Transcript editor's note: At the beginning of the debate Zeilinger's chair was vacant—but he did turn up later.

[2] Transcript editor's note: Jack Tuszynski was invited to be on the panel but unfortunately called in sick, so Derek Abbott substituted him at the last minute.

as opposed to the Yes Team, and this is perhaps a suggestion to the audience that maybe you should look for the wow-factor at the end of the debate when I will ask for an informal vote on whose side was the most persuasive. If you have been wowed by something that the No Team said that the Yes Team did not manage to make sound totally mundane, and so forth, then [consider this in your voting decision].

So, the format that we are going to adopt is the following. First, we will start with the No Team presenting their case, each panelist will speak in turn only for three minutes, and then we move to the Yes Team, again three minutes each. Then [in order to] reply we return again to the same order—limited to two minutes for panelists, and then at the end of that I would like to go one more round to give each one of the panelists a chance to summarize his position in two sentences. After that we will take questions from the audience for the panelists and then I will ask for an informal vote. I hope the panelists summarize their points from their talks yesterday. I apologize to the panelists for having missed the presentations of Wednesday, because I haven't mastered the quantum mechanical art of being in two places at the same time. Unfortunately, I just couldn't. I hope they will be kind enough to repeat the things that they might have said in their talks that might be relevant to [today's] subject as I would very much like to learn myself. So without further ado, let's start with the No Team: Professor Davies.

Paul Davies (No Team): Thank you. Well I'm sorry to disappoint you but I was particularly *not* going to repeat the content of my lecture on Wednesday morning, where I set out what I felt were the most persuasive arguments on the grounds of science for the non-trivial effects in biology. I thought I would restrict my remarks, this evening, to addressing a more philosophical point as befits a professor of natural philosophy. The problem of the origin of life remains one of the great unsolved problems of science, and that in itself is a highly non-trivial problem. The simplest living thing is already so immensely complex—[when you consider] the first living thing that arose just from the random shuffling of building blocks of molecules—that it is quite clear that the odds against that happening are so stupendous that it would have happened only once in the observable universe. It will in fact be a near miracle. The alternative is that life is a natural and more or less automatic part of the outworkings of the laws of Nature; in which case there must be some sort of life-principle, or what the Christian de Duve calls a "cosmic imperative." And if there is such a principle then this principle must exist within physical theory. It must be a part of physics and, though we haven't deduced this principle yet, we imagine that it is something that is incorporated within physics; and then the question arises: Does that life principle come from quantum physics or is it part of classical physics? I can give three reasons at least why I think it will be part of quantum physics. The first is that quantum mechanics is, of course, a fundamental theory; the idea that you can choose the world as classical or quantum mechanical is nonsense. The world *is* quantum mechanical. We live in a quantum mechanical universe, so quantum mechanics is the *default* position. If we are looking for a new principle in physics—by default it belongs in quantum mechanics , or else quantum mechanics is *not* the correct description of the world.

The second point is that life, of course, proceeds from the quantum world. Life is ultimately molecular and it must have begun in the molecular domain. And so life came out of the quantum domain, and to insist that the quantum domain somehow had to stop or that one had to move beyond it before life came to exist, seems to me to be completely unreasonable. The third point of view—I'll mention it very briefly, famously introduced by Eugene Wigner—is that the connection between life and quantum mechanics is there all along in the role of the observer. Of course, we are all persuaded that wave functions don't collapse [due to conscious agents], [rather] they decohere by the environment—but, as Anton Zeilinger said so clearly in his lecture,[3] we're still left with the issue that quantum mechanics is incomplete inasmuch as it gives a probabilistic description of the world and the actual outcome of any given observation clearly depends on the observer. So, I think that the other team had better state, first of all, whether they think life is a miracle—and if it's not a miracle, why is it that the life-principle, which must be there, is disconnected from fundamental quantum physics? What sort of principle emerges only when wave functions decohere? That's what I'd like them to answer. Thank you.

Gea-Banacloche (Chair): I will try to stand up and signal that it is 15 seconds before the end.

Stuart Hameroff (No Team): Thank you. Real-time activities of living systems are all performed by conformational fluctuations of proteins, changing shape on the order of nanoseconds. How do proteins control their shape? Within proteins high energy charge interactions tend to cancel out. So functional dynamics are governed by collective actions of numerous quantum mechanical van der Waals-London forces, influenced by external factors. London forces are instantaneous dipole couplings of electron clouds in non-polar amino-acids, which form non-polar hydrophobic pockets within proteins. These tiny pockets—where quantum forces rule—are essentially the 'brain' of each protein. Thus proteins—at least certain proteins—are quantum switches, which should exist for some time in a superposition of conformational states. Protein qubits: why would Nature need qubits? Quantum computing is the answer, I believe. Geometric lattice assemblies of protein qubits, for example, microtubules, are well-suited to act as quantum computers. The evolution of organisms utilizing quantum computation would have enormous advantages.

Is there evidence of quantum computation in biology? If any of us needed surgery, say our appendix ruptured, we would be anaesthetized, rendered non-conscious by breathing a gas mixture containing roughly one per cent of an anaesthetic gas molecule, which is inert. These molecules float from our lungs into our blood and brains selectively and act at the same hydrophobic pockets, which govern the dynamics of certain proteins in our brain. They form no chemical bonds or ionic interactions, acting merely by the same quantum mechanical van der Waals-London forces, occurring naturally in these proteins, thereby preventing the normally occurring London forces, inhibiting protein quantum switching in the brain and erasing consciousness. [Other brain activities continue.] The surgeon takes his knife and we feel nothing. So consciousness—the most elegant biological process—utilizes quantum processes quite possibly quantum computation. Other functions like immune cell recognition, cell division, etc. may also utilize the unitary oneness of quantum coherence and entanglement.

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[3]Transcript editor's note: Jennewein, T. and Zeilinger, A. (2004), Quantum noise and quantum comunication, *Proc. SPIE Fluctuations and Noise in Photonics and Quantum Optics II*, **5468**, pp. 1–9.

Ah! The decoherence! Biology is warm and wet—it's very warm. Yes, but bio-systems may utilize laser-like coherent phonon-pumping from a heat-bath of biochemical metabolism. Several months ago a paper in *Science* by Ouyang and Awschalom[4] showed quantum spin transfer between quantum dots connected by benzene rings—the same type of [electron cloud] ring found in hydrophobic pockets. The quantum spin transfer was *more* efficient at higher temperature. Benzene rings are identical to the electron resonance rings of the amino-acids found in hydrophobic pockets in proteins.

Wet—yes, we are mostly water, but cell interiors exist much of the time in a gel state in which all water is ordered, coupled to protein dynamics. Additionally structures like microtubules can use Debye layer screening and topological quantum error correction—that is, utilizing the Aharanov-Bohm effect as suggested for quantum computers by Kitaev. In conclusion, whether quantum processes evolved as an adaptation of biology, or whether biology and consciousness [evolved as] classical adaptations of pre-existing quantum information, they [may be] like artificial neural networks, [which were copied after] brain systems in the 80s. Quantum information technology can learn a great deal from the study of certain biomolecules.

Julio Gea-Banacloche (Chair): Thank you, and that was a little long, but I don't mind perhaps giving this team a little more time since they are slightly handicapped here...

Audience laughter

Julio Gea-Banacloche (Chair): ...by the absence of one person [Anton Zeilinger]. Thank you for addressing the drugs question too.

Audience laughter

Julio Gea-Banacloche (Chair): Moving on...Derek.

Derek Abbott (No Team): OK, the position I'm going to take in this debate is one of cautious optimism and my question I'm going to put to the Con Team is: Why not explore the relationship between quantum mechanics and biology? Why not have a go? It might be fruitful because, when you think about it, Nature has been around for 3.5 billion years and it's produced some marvelous, fascinating things that we don't understand. It's often said that Nature is the world's best engineering text book. Anything Man sets out to go and do technologically—if he looks at Nature first—he will always find examples beforehand carried out by Nature [often] even better than we can do. So my challenge to the Con Team is to think of a counterexample and actually tell me something that Man has invented that Nature hasn't. So, if this is true, then it's hard to believe that Nature hasn't [already] made clever use of quantum effects.

Now, there are two people that have famously made a counter-example to [the standard] argument that I've made, and one is John Maynard Smith, and the other is Charles Bennett. And I'm going to take on these guys one by one now. So, Maynard Smith says that Nature has never used the wheel—Man has invented the wheel, but Nature hasn't. Now of course he's wrong because bacteria have flagella, which have true 360 degree axes of rotation! Maynard Smith visited [my lab at]

[4]Transcript editor's note: Ouyang, M. and Awschalom, D.D. (2003), Coherent spin transfer between molecularly bridged quantum dots, *Science*, **301**, pp. 1074–1078.

The University of Adelaide 3-4 years ago and actually admitted this oversight. Also, Charles Bennett famously commented that Nature has never made explosives and has never made the radio, but this of course is wrong as well. For example, there is the bombardier beetle that excretes a gas that explodes when it hits the air, to keep off its predators. Also, Nature invented the radio as well. The example is fireflies; when they're [about to] mate they modulate an electromagnetic signal—in other words they flash on and off—and the female receives that message. And so that's a radio—it's [albeit] a slightly different wavelength.

Audience laughter

So, anything that you can think of biology has already thought of it. So, if these team members, over there, really believe in quantum computation—and I assume they do because they've actually made quantum computers to a few qubits, so they must believe in it—then Nature must have 'thought' of it or used it in some way first.

Just finally, to finish off, I want to remind the Con Team that Carlton Caves—their quantum information guru—is on record as saying that because Nature is so clever, there possibly is a very small chance that Nature, through natural selection, may have found some use for quantum decoherence-free subspaces.[5] And so I would just like to leave it at that point.

Julio Gea-Banacloche (Chair): Thank you, Derek. I just want to remind the No Team that this team is actually a Yes Team, not the Con Team. I realize that is confusing but...

Audience laughter

Anyway, thank you very much to all of you and now we are going to hear what the Yes Team has to say ...

Jens Eisert (Yes Team): Well then, I suppose it's up to me to open the case for the Yes-No Team...

Audience laughter

Jens Eisert (Yes Team): ...well, unless someone expects me to volunteer to fill in for Anton Zeilinger on the other side. Well, let me start with some numbers and science, rather than the philosophical issues raised before. It seems that in the whole debate the 'make-or-break' issue is whether coherence can be preserved over the timescales relevant for non-trivial biological processes. And of course, one has to say what one means by non-trivial here. Needless to say, everything in biology is built via quantum mechanics—bonds, hydrogen tunnelling, and so on. But, however, if one regards living entities as information processing devices, one could make a definition of 'non-trivial' that this kind of information processing is in some form quantum information processing. There I would doubt whether coherence can be preserved over timescales that would be relevant to have efficient quantum computation—in the sense that it is discussed in [the field of] quantum information. In a nice paper by Tegmark[6]—where he looks at the decoherence timescale in a simple model of neurons firing or not—for a neuron to fire or not

[5]Transcript editor's note: see Chapter 15, p. 384, of this book.

[6]Transcript editor's note: See Tegmark, M. (2000). The importance of quantum decoherence in brain processes, *Phys. Rev. E* **61**, pp. 4194–4206.

means that 10^6 sodium atoms are on one side of the brain or the other side of the brain. If one just looks at the neighbouring sodium atoms then the decoherence timescale just from simple high-temperature Brownian motion gives a lower bound of 10^{-20} seconds, which is very, very short and even if one [considers] very low levels for decoherence timescales in microtubules inside the cytoskeleton, then the most conservative bounded scheme is 10^{-30} seconds for a typical decoherence timescale. So, I mean in the light of this, it seems fairly unlikely that something non-trivial as quantum information processing [appears in] biological syst ems.

Let me remark on Paul Davies' [point] directly. What he would suggest is that [a quantum process in] life is some sort of fast-track to the early emergence of life. There are two points [I can make]. If one thinks of searching—well, if it's a quantum search there must be some sort of oracle that says, "OK, you have life, or you do not have life," so—the point is also that everything must be coherent all the time. One thing is, what must be coherent over all generations so that we have the superpositions of us, our kids and our kids' kids, and so on, and they do not cohere in order to have a proper fast-track to life—and then, my final point: there's the teleological point that, hey, we search for something—but first point—one has to specify is what one looks for when we're searching. So, it doesn't seem entirely clear what the search is for life, because the pay-off is not clear. It is not clear what one in fact is looking for.

Julio Gea-Banacloche (Chair): Thanks, Jens. Howard.

Howard Wiseman (Yes Team): Thanks Julio. Okay, so to begin I would just like to say that the Yes Team in this debate obviously wins by default. The topic is debating "Quantum effects in biology: trivial or not?"—well, clearly the answer is yes, they are trivial or not ...

Audience laughter

Howard Wiseman (Yes Team): ... No, seriously, I think the point is that, yes, you do need to look at the title of this debate carefully and the keyword in my mind is "trivial." I'm glad that people see that people are taking this in a good spirit, and indeed claiming things to be non-trivial that I would agree are non-trivial. There are a number of people that have said that obviously quantum mechanics is behind everything, but Julio said that what he is really looking for is for the No Team to come up with something *surprising*. I guess I think a word or a note of warning is necessary here: that what physicists like Julio and many of us here are surprised or interested by here are notoriously obscure: the fact that we're all here at a conference called *Fluctuations and Noise* would be very surprising to most members of the public.

Audience laughter

Howard Wiseman (Yes Team): So, I think a better definition, of what is non-trivial, is not what will surprise and interest physicists but, rather, something that would convince a biologist that they need to learn quantum mechanics. A non-trivial quantum effect in biology is something that will make a biologist want to go out and, you know, take a second year quantum mechanics course and learn about Hilbert space and operators, so that they understand what's going on. That's my concept. Now, again, we all seem to be in agreement that an obvious example of this is quantum information processing: that this is somehow the heart of what we're getting at here, because what most people involved in biology are interested in these days is information processing in some form—in control, in genetics, in cells, in thoughts, in consciousness, and all of that is information processing. So something non-trivial would be whether there's quantum information processing in there. So, needless to say, I don't believe there is.

To respond to some of the points of the No Team so far, Paul Davies said he wants the No Team...er...I mean...Yes Team to respond to his challenge of explaining where the life-principle comes from—that is supposed to be a new principle of physics. So, I have two responses to that: (a) I don't believe there is one, and (b) I think that it's outside this debate, so it shouldn't be talked about at all. Firstly, I don't believe it because I think it comes from the fallacy that "I don't understand A, I don't understand B. Therefore, A and B must be the same thing." And secondly, I think it's outside the realms of debate. This debate is about quantum effects, not about effects that result from some new theory—that we don't even understand yet—but which has something to do with quantum mechanics. I think this remark is also directed at Stuart Hameroff's ideas that involve quantum gravity and things that don't even exist yet in theory. I guess I'll leave it at that.

Anton Zeilinger enters the room

Julio Gea-Banacloche (Chair): Right, I'll take a break to welcome Anton Zeilinger. I'll probably let him have some four or five minutes in the next round. But now, to keep going with the flow, the third member of the Yes Team: Sergey.

Sergey Bezrukov (Yes Team): Thank you. I think that everybody is too serious for this late hour, so I decided, instead of sticking to my introduction and answering questions, to tell you an anecdote. This anecdote is a real true story, which happened about twenty five years ago at the NIH—National Institutes of Health—campus in Bethesda. The story is that one young post-doc—actually a candidate who looked for a post-doctoral position and who is now a well-established professor at the University of Maryland and, by the way, came to be a very famous scientist (I would tell you all the names if I did not know that Derek is going to publish all this).

Audience laughter

Sergey Bezrukov (Yes Team): Anyway, [this young man] came to the famous scientist (anyone of you, who ever did anything in rate theory knows his name for sure) [looking for a job]. And he was told "Okay, I like what you're saying, I like you, so I think am offering you the job, but please remember that $\hbar$ in Building 5 is zero".

Audience laughter

Sergey Bezrukov (Yes Team): And all I have to add here is that after 25 years, $\hbar$ in Building 5 (where most of the physicists at the NIH sit) is still zero. Now, I agree completely with what Paul just said. Of course, life is a non-miracle, it follows from physical laws, but if quantum mechanics plays a decisive role in the explanation of the life phenomenon I'm not sure about this; [I say "not sure" rather than "no"] because it is very dangerous to say "no" when talking about science. As for Stuart's short speech, I can say all those fluctuations that he was talking about are pretty well understood from the point of view of classical physics; there is no problem in all of this. In his talk [at this conference] Prof Frauenfelder [was discussing the] timescales of these fluctuations and the timescales are understood [in the framework of classical physics]. Thank you.

Julio Gea-Banacloche (Chair): Thank you.

Hans Frauenfelder (Yes Team): I think as an experimentalist I would only start looking for non-trivial quantum effects if I find something that I cannot explain in any other way—but since we have started in telling stories, I have a story about what is trivial. Frank Yang, the Nobel Prize winner, gave a talk in Seattle many years ago and he said, when discussing a particular point, "It is trivial." He was challenged by another physicist, Boris Jacobson who asked, "Is it really trivial?" After the talk they went back to the office of Boris, worked for two days and they came out agreeing that it was trivial.

Audience laughter

Hans Frauenfelder (Yes Team): Some of Paul's statements sound to me like religion and it's very hard to discuss religion. Two statements about the fluctuations—I probably know as much about fluctuations as most people—and I've never yet seen something that looks like a miracle. The fluctuations that we observe are explainable using standard physics. At the moment, I see no reason to invoke something that's supernatural or quantum mechanical in the understanding of biology.

Julio Gea-Banacloche (Chair): Thank you and that finishes the first round, so everybody has now two minutes to reply, except for Professor Zeilinger who can have 5 minutes. Thank you.

Paul Davies (No Team): Let me just respond to a few of these points. First of all, is my position religious? I would say that it is exactly the opposite—[it is the person] who says that life originates because of some stupendously improbable set of events [who] is effectively appealing to religion by calling [life's origin] a miracle. There's no real difference between a miracle and an event that is so improbable that it's going to happen only once in the universe. So I think by saying that there are principles in physics, which encourage matter to organize itself into life, is the scientific position. We don't know [this hypothetical principle] yet, but to [claim] perversely that this principle does not belong within quantum mechanics seems to me a very peculiar position. As far as the teleological aspects are concerned, I think that's very easily dealt with because the physicist will define life as a system that would replicate, which is a well-defined physical criterion. The pay-off for the system is that it gets to replicate—so that takes care of that point. And I've probably used up my two minutes—well, I think I've got nothing else to say!

Audience laughter

Paul Davies (No Team): ... because I'll defer to Stuart on the question of timescales for decoherence.

Stuart Hameroff (No Team): First of all, Jens, I'm glad you read Tegmark's paper; unfortunately you didn't read our reply to Tegmark.

Audience laughter

Howard Wiseman (Yes Team): [You mean in] *Phys. Rev. E*, the same journal as your paper?

Stuart Hameroff (No Team): Yes, *Phys. Rev. E*, the same journal that he published in. Tegmark successfully disproved his own theory about microtubules [implying] that he was disproving ours. However, his decoherence time of 10^{-13} [seconds] was based on a superposition separation distance of 24 nm, whereas our [superposition separation distance] was a Fermi length—so that's seven orders [of magnitude lengthening of the decoherence time] right there. He also neglected things like dielectric, [permittivity], Debye layers, and [decoherence free sub-spaces] and some other things. We corrected for those, we used his same formula, and we got [the calculated decoherence time] to 10-100 milliseconds. If you add the potential effect of topological quantum error correction you get an indefinite extension. As far as the comments about the fluctuations of the proteins not needing any miracle, quantum effects are not supernatural. It may seem that that protein dynamics is [straightforward and classical], however, as I mentioned, the biochemistry text, by Voet and Voet, clearly states that the strong forces cancel out, and the weak London forces rule on timescales relevant to conformational fluctuations. Also, [in] Professor Frauenfelder's lecture in his wonderful work on myoglobin, he showed a xenon molecule, which is an anaesthetic, exactly like [the other inert anesthetic gases we use clinically]. [Xenon is] a perfectly good anaesthetic, we [could use for patients] to go to sleep for surgery. It's expensive but it works just fine. It's completely inert and neutral; gets into hypophobic pockets and does exactly what the other anaesthetics do [binding only by quantum London forces]. Professor Frauenfelder has said that xenon prevents the dynamics of myoglobin, so while he was looking at the other effects and attributing [protein conformational control] to external classical fluctuations rather than internal control. [Control of myoglobin may be mediated thr ough quantum London forces in a hydrophobic pocket blocked by xenon]. Thank you.

Anton Zeilinger (No Team): OK, first I would like to apologize it's my fault that I didn't realize that the debate was moved down by half an hour. I had the old schedule, but this is my fault and I apologize for this happening. Now, let me make one or two statements. I have no idea whether quantum states play a trivial or non-trivial role in biological systems; otherwise I might not be sitting here. But I feel that there is no reason why they should not. And as an experimentalist I view—I see a challenge—to prove that quantum systems basically no matter how complex can exist in quantum superposition. This is independent of the question of whether this plays a role in living systems or not but my fervent approach is, that if we are able to prove that quantum superpositions can be shown in the laboratory and later on for very complex systems including living systems, it might change the way biologists view their own business, because biologists' essential paradigm is that we are essentially classical machines.

Now I am saying—in including living systems—I do not see any reason whatsoever why we should not be able to see a quantum superposition of bacteria, for example some day. I know that all the papers which talk about, you know, decoherence, about coupling linking systems with environment, and why this would not allow quantum interference—I read such papers as instructions about what *not* to do and how to avoid decoherence. For example, this specific thing, which I am sure will be done in the future—I don't know when—is that you take a small living system, say a bacterium provided with other technology with its own living shell around it, so that the whole system does not couple to the environment, and then I'm sure you can put the whole thing through a double slit or whatever. There is no reason not to have quantum superpositions of living systems. As I said this might change the viewpoint of people. It might really lead to something new. The question is certainly interesting and whether [quantum effects are] trivial or non-trivial in living systems and what is called for is something like Bell's theorem. It is also under-appreciated, how gigantic the achievement of John Bell was. Namely that he was able to give a general set of quantified criteria, which tells you whether in a given situation, you can explain what you observe, by a local, realistic viewpoint. We need to see exactly the same kind of thing for a living system. So, if somebody would be able to provide criteria which tell you if a certain condition is met, we know that quantum phenomena play no role in living systems that would be an equally important achievement as the opposite [viewpoint]. It might be possible, it might not be possible, I have no idea whatsoever...

Julio Gea-Banacloche (Chair): Not much time left for you.

Anton Zeilinger (No Team): Alright I should give the rest of the time to others, but I just would like to point out one more thing. Suppose we have some dynamics, which release two coherent superpositions in living systems. No matter for how short a time, then my claim is that decoherence does not [matter]—because decoherence gets rid of non-diagonal terms in the density matrix, but it does not explain to you why a specific event the living system happens and we are dealing with living systems in relation to each other. Finally I want to share with you something I learned from yesterday, and in the quick discussions we had about today's debate. It would be extremely non-trivial if quantum mechanics did not play a role in living systems, it would be the only area in which we know quantum mechanics is not at work. Thank you very much.

Derek Abbott (No Team): Just in rebuttal to the Pro Team...I get confused...so I'll call them the Fundamentalist Team. So I find it surprising that they take their particular position. I'd like to remind Jens Eisert of one of his own papers, where he motivated the idea of quantum games as perhaps helping to explain how Nature might play quantum games at the molecular level.[7] So this leads to an interesting point that perhaps quantum mechanics might—if it doesn't [already play a non-trivial] part at the biological level—then what about the [evolutionary] pre-biotic level? So that is another thing I'd like to throw out to the Con Team... er... Fundamentalist Team. And I'd also like to remind them that they haven't yet found a counterexample to my little conundrum I made the first time. Thank you.

Julio Gea-Banacloche (Chair): That was short. Alright, Jens you may as well address your guilty past.

Audience laughter

Jens Eisert (Yes Team): I don't want to: that's my game. OK, we'd better start with Anton—there seem to be three things that need to be addressed and

[7]Transcript editor's note: Eisert once speculated about non-trivial quantum effects at the molecular level. See Eisert, J., and Wilkens, M., and Lewenstein M. (1999) Quantum games and quantum strategies, *Phys Rev Lett.* **83**, pp. 3077–3080.

need to be done, in order to have a meaningful debate. And that's, in my point of view: experiments, experiments, and experiments. What I would like to see, for example, is [based on] some of the arguments that we were discussing are in principle explainable. So I would like to see, say, an experiment where you prepare entangled photons, let them be absorbed in a photosynthesis reaction, the energy is transferred to internal degrees of freedom, and then you have a Bell inequality violated. The point is that, some of the statements about coherence are testable in principle. It only becomes difficult if one thinks of processes that are underlying other processes that are so much larger than the things you're talking about. To Stuart, and if you look for, say, the effects of gravitational objective state reduction, it looks beautiful to do experiments to confirm or to falsify the hypothesis made in this context, but I mean, if the effect you're looking for is orders of magnitudes smaller than the environment induced decoherence that you have, then I would rather like to see an experiment that first deals with the numbers that are there and are accessible by experiment. And then, what about timescales? I liked Howard's comment on the A and B. One needs to be careful of the fallacy that, well, if A happens on timescale something and B happens on timescale something, therefore A must be B. You have decoherence processes happening on, say, one second—which happens to be decoherent—and our thought processes happening on the level of one, then we should not be really tempted to say it is the thought process.

Three, concerns the search for life, I mean, if one is really searching for life and the goal is to have a successful species in the end of maybe if you want to, you can have a quantum strategy or whatever. I mean, this concludes that there are so many rounds going on with the generations, this has to be coherent. I find it hard to imagine that the power to replicate or to have a powerful species again can play any role in the search for life on the quantum level. My time is up.

Howard Wiseman (Yes Team): So yeah, in terms of counter-examples to Derek's claim, it seems to me a ludicrous suggestion that Nature has developed every technology that you can think of. And yes, I just thought of four things here, which to my knowledge, Nature hasn't done: an internal combustion engine, a television, a refrigerator, an inferometric measurement of gravity.

Audience laughter and applause

Howard Wiseman (Yes Team): So, to move on—oh, Anton—Anton said that in his experiments that there is no reason that quantum effects couldn't play a role in biology. I would say if that's the case, Anton, why don't you do your interference experiments in a saline solution? Warm, wet... my point was, why do you do yours in a high vacuum rather than in a warm, wet environment? OK, so to go back again to what Julio began with by asking: he not only asks to be surprised, he asks for the No Team to provide surprising *facts*. I think that's one thing that's been lacking. You have surprising *speculations* ...

Audience laughter

I'd like to make a comment specifically for Stuart: the word 'coherent' and the word 'quantum' are not synonyms. So you can have coherence without having quantum effects. I think that's a very important point. OK, in terms of whether there's quantum computation going on in the brain, I think it's an *enormous* leap of faith to believe something like that. To begin with, in Stuart's scheme involving tubulin proteins, as far as I know—I would like to know if I'm wrong—there's no evidence that tubulin even does *classical* computations, still less that it does quantum computations, and even *less* than it does quantum computation that involves general relativistic effects. So I think this theory is so far ahead of the experiments that it is fairly pointless.

OK, another point about why we are skeptical about quantum computation happening in the brain is [the following]. An important point about quantum computation is that it is useless unless you have a real large-scale computer—because quantum computers are very hard to build and they tend to be slower than classical computers. So you only get an advantage out of them if you can actually get to a very large scale, and then finally quantum computers are going to be faster than a classical computer. So how a quantum computer could ever have evolved, as it's completely useless until it's extremely large? And my time's up.

Sergey Bezrukov (Yes Team): I would like to comment on Prof Zeilinger's last statement where he proposed that "it would be very surprising if quantum mechanics has nothing to do with biology."

Anton Zeilinger (No Team) [Interjecting]: I did not say "surprising," I said "non-trivial."

Sergey Bezrukov (Yes Team): Okay, I meant "non-trivial." Anyway, quantum mechanics has actually a lot to do with biology and it was a problem for me [to decide] on which side of the debate to join. [This is] because my only point is that quantum mechanics as of this moment hasn't provided any *qualitatively* new insights into the mechanisms [studied by] biological physics. At the same time, it has great importance in the *quantification* of many phenomena at the elementary level. And the best example to discuss is probably van der Waal's forces, because to explain van der Waal's forces one doesn't need any quantum mechanics. If you know the history of the subject, the first explanation, the first qualitative explanation of van der Waal's forces, belongs to [the Russian physicist] Lebedev [who worked it out] more than hundred years ago. There was not any quantum mechanics at that time. However, to calculate with reasonable accuracy the constants of interaction, one has to have the quantum mechanical input. So what I'm saying is that up to now—and I don't know what is going to happen in the future—but up to now, "$\hbar$ is zero" for the reason that quantum mechanics did not supply us with any qualitatively new insights about the molecular mechanisms in biology. At the same time [quantum mechanics] is of greatest importance for quantifying [the] dynamic interactions, including interactions [involved] in protein folding [and functioning].

Hans Frauenfelder (Yes Team): First of all I have to remind the audience that the roles we play in here have been pre-assigned, so we cannot be accused of being a believer or non-believer.

Audience laughter

Hans Frauenfelder (Yes Team): The second point is quantum mechanics is absolutely essential for biology. There is no question. For instance electron transfer occurs in quantum mechanical tunneling—it is essential. I think that the question which we're really discussing hasn't been clearly stated is: "If we find a general law that determines or explains life, is it quantum mechanical or classical?" Here I have no opinion and I will wait till it is discovered.

Julio Gea-Banacloche (Chair): Thanks to all the panelists. I think that they have raised lots of interesting points, on both sides, and I'm sure that the audience will have many questions. Yes, we'll have a two sentence summary and so, Paul.

Paul Davies (No Team): I just want to respond to Jen's point about remaining coherent, generation after generation. That's certainly not what I had in mind. Just getting the first replicator seems to me is very hard. Quantum mechanics would potentially be very useful for [acting over fractions of a second to avoid] hanging in there for thousands of millions of years. To sum up, I would say that quantum mechanics is the default [option] and until somebody persuades me that it's not [part of] the origin of life, I think that's the only reasonable thing to assume.

Stuart Hameroff (No Team): OK, well, in the first of two very long sentences I want to respond to the chairman's point about (a) drugs, and (b) consciousness, which were brought into the discussion. In the '70s it was shown that the potency of the psychedelic drugs was proportional to their ability to donate electron resonance energy to their receptors, suggesting that receptors are more prone to go in the quantum state, suggesting further that the psychedelic experience might use quantum information, and I might add that psychoactive neurotransmitters like serotonin and dopamine also have electron resonance effects. The second sentence is that aspects of the subconscious including [dreams] are increasingly being expressed in terms of quantum information, that the subconscious mind is to consciousness what the quantum world is to the classical world.

Anton Zeilinger (No Team): First, one little remark on Howard's remark on my remark: "Why don't we do our experiments in saline solution?" And I guess I pointed out that someday we hope we can do these experiments, in quantum superposition, with living things including the saline solution. So it might simply be that the picture is a little bit too narrow. If we dissect a living system to the centre of the saline solution to the brain and it is clear that information goes back and forth to the between all kinds of components in there, and may be we should do that and we should include those kind of considerations somehow. I know there are all kinds of reasons why this is stupid, but there might be a reason—it may work some time. The second point, the second sentence, I would like to mention—I think Howard's argument against some of these that they are far ahead of experiments that some scientists have been discouraged about what us experimentalists can do. I mean I saw it happen in the field of quantum information. People simply didn't think about ideas or writing them down, because they thought the experiment was not possible or the experiment too far ahead. You never know how fast we can move and in which direction—this might be true in this area too, I hope.

Derek Abbott (No Team): Howard's[8] refrigerator: the principles are there and animals cool themselves down by sweating, by evaporation. The internal combustion engine: Howard's stomach when he eats and consumes food—the principles are there. Television: the principles of encoding information and transmitting it through electromagnetic radiation are there—that's the firefly example. As for detection of gravity waves: wrong scale in biology. That one doesn't count.

Audience laughter

[8]Transcript editor's note: This refers to Howard Wiseman

Derek Abbott (No Team): I would like to make an observation now, in my summary. I would like to make an observation that, you know, our team has been pro-active whereas the other team has been reactive. They haven't come up with any interesting stuff.

Audience laughter

Derek Abbott (No Team): ... we're the interesting team!

Audience laughter

Julio Gea-Banacloche (Chair): Your two sentences are over.

Derek Abbott (No Team): The question of quantum mechanics in biology: it's a fascinating question—so in summary, I want to say: let's stop being armchair scientists, let's apply the scientific method, let's go out, and let's do some experiments in the spirit of what Anton is saying. We may—if we do this—we may just find *something* that Nature can teach us about quantum computation.

Julio Gea-Banacloche (Chair): Well, these have turned out to be rather long sentences, but...

Audience laughter

Jens Eisert (Yes Team): To start with, Nature has television, but does Nature also have game shows?

Audience laughter

Jens Eisert (Yes Team): OK so we are on the boring side, but something seems to be buried. There seems to be some sort of psychological belief that the mystery of life sounds cool if some sort of quantum effect is involved. I must say that I'm not very happy if the brain just works as a classical Turing machine—admittedly—and not that happy that the brain is a quantum Turing machine either.

Howard Wiseman (Yes Team): OK, I just want to say, quantum information processing is *extremely* hard to do and as far as we know, it's only used for solving obscure number-theoretical problems.

Audience laughter

Howard Wiseman (Yes Team): I'd be happy for the experimentalists on the other team to find evidence for [non-trivial quantum effects] in biology, but I don't believe it so far.

Sergey Bezrukov (Yes Team): Just in two sentences. Quantum mechanics will be very important for the future development of the biological physics, or 'physics of biology', but up to now the situation is very simple. As I told you already, [quantum mechanics is of] great importance for the quantitative understanding of the [basic interactions and] processes' rates, but, unfortunately, [of little importance] for the qualitatively new insights and new concepts. Thank you.

Hans Frauenfelder (Yes Team): I think essentially everything has been said, and I am concerned with summarizing. The answer is we need experiments to answer the question, but first we have to find out what the real question is, and we haven't done that.

Audience laughter

Julio Gea-Banacloche (Chair): Well, I would like to thank all the panelists again, and now we have questions from the audience. Ah, there is one!

Laszlo Kish (Texas A&M): Just a short comment: Paul didn't take the 'trivial' part seriously. The question was about *non-trivial* quantum effects. Anything that refers to material properties, dead material properties: chemistry, tunneling, van der Waals forces, even if it is quantum, is trivial because still occurs in dead non-living material.

Julio Gea-Banacloche (Chair): Does anybody want to address this point?

Paul Davies (No Team): I dread to reopen the whole debate about what is trivial and what is non-trivial, as it is a non-trivial topic.

Audience laughter

Peter Heszler (University of Uppsala): I just have a comment that, as far as I know, if you take high quantum numbers, quantum theory converges to classical theory. My question is: "Are [humans made up of materials] with high quantum numbers or low quantum numbers?" Because if we are high quantum numbers—apparently according to Bohr—we are classical. If we are low quantum numbers, then we are quantum mechanical. That's my point.

Anton Zeilinger (No Team): I would simply disagree with your starting point. The limit of high quantum numbers is not always classical.

Juan Parrondo (Universidad Complutense): It looks like when we're talking about the brain here, the only way to escape from this picture of the brain as a classical Turing machine is going to the quantum world. I would like to say that there are other ways of escaping from the Turing machine: for instance [by appealing to] chaotic classical systems or [by appealing to] recent studies of treating the mind-body relationship as a whole. [Thus] I think there are other ways of escaping from this narrow aspect. This is a kind of an off-side comment.

Stuart Hameroff (No Team): I'll cover that now. I got interested in Roger Penrose's argument using [Gödel's] theorem that human consciousness uses something that is non-computable. Still deterministic, but not algorithmic and chaotic systems and everything you said are still basically deterministic and algorithmic. The only way out of that is something that he called non-computable and he brought in his hypothesis of quantum gravity, which is the only way out of us being helpless spectators and conscious automata. And [Jens Eisert] mentioned how seemingly ludicrous it is to bring in quantum gravity because [the energy] is 24 orders of magnitude lower than [the environment], however, in Roger [Penrose's] scheme the reduction is instantaneous so the power is actually calculated as a kilowatt per tubulin protein.

Unknown (Audience Member): You say that it's instantaneous?

Stuart Hameroff (No team): If you approximate "instantaneous" to one Planck time, you take the very low energy divided by the [even smaller] Planck time of 10^{-43} seconds, giving a kind of a karate chop.

Anton Zeilinger (No Team): Why don't we all boil if it is a kilowatt?

Stuart Hameroff (No Team): Because [the energy is delivered] only over a Planck time of 10^{-43} seconds.

Jens Eisert (Yes Team): In the mid-19th Century as far as I know there was this debate whether there's something special about this kind of energy of life or not...er...I only know the German word—very sorry—a kind of spirit of life specific for...

Derek Abbott (No Team): 'Vitalism' [is the word you are looking for.]

Jens Eisert (Yes Team): Ah, vitalism. Okay, if one pushes that picture so far, then one can just speak of consciousness particles that are in the brain and then we are done. If you go beyond the theories that are open to empirical verification [then you have gone too far].

Stuart Hameroff (No Team): You're putting words in our mouths, we didn't say that—although I will admit to being a quantum vitalist—but it's not that we have quantum particles, it's that [biology utilizes quantum superposition, entanglement and computation. Why wouldn't it?]

Unknown (Audience Member): What quantum information processing could be useful in biology?

Paul Davies (No Team): If quantum information processing is not useful, why is so much money being spent on trying to improve it?

Audience laughter

Paul Davies (No Team): Quantum information processing bestows upon Nature awesome information processing power and I would find it totally extraordinary if in the entire history of the universe this has never been put to use until now.

Unknown (Audience Member): What is the one example? One possible example?

Paul Davies (No Team): Well, we naturally look to Nature's great information processing system which is called life. Really, for me, that is the most persuasive point. Where else would we expect to see this happening in Nature, except life, which is just so wonderfully adept at processing information? And [according to orthodoxy] we are to suppose that life hasn't discovered the awesome information processing power that quantum mechanics provides—but that's all gone to waste over the 13.7 billion year history of the universe and it's only *now* that human beings have discovered [quantum information processing]. That seems extraordinary hubris.

Stuart Hameroff (No Team): Just think of your subconscious mind as being quantum information, which 40 times a second collapses or reduces into your conscious mind.

Unknown (Audience Member): In order to live you've got to have very large redundancy because you are constantly attacked by microbes, viruses with all kinds of things—if I use my glasses it is because I see not so well. Quantum information seems to be very, very fragile. Whatever you do, a small perturbation and the whole computation fails. If quantum computation has anything to do with living [systems], it seems to me that Nature should have found the optimal quantum error correction scheme. So maybe this is what we should be [looking for.]

Paul Davies (No Team): Yes, they may indeed to have done so and it seems to me very sensible to look at Nature's nanostructures within cells to see if they are deploying any tricks that we could make use of.

Stuart Hameroff (No Team): I mentioned [yesterday] that microtubules seem to have used the Fibonacci series in terms of their helical winding and it has been suggested that they utilize a topological quantum error correction code that could be emulated in [man-made] technology. As far as redundancy, there is a lot of parallelism in the brain and memory seems to be represented holographically, so redundancy is not a problem.

Jens Eisert (Yes Team): My concern with quantum error correction is that some care is probably appropriate. I mean it's not known what the actual thresholds are for quantum computation against arbitrary errors and if you take off your glasses it is not so clear what errors are going to come against you. But the best known bounds on the 'market' are 10^{-4} for quantum computation. And so we need to see the perspective that really small errors can be corrected with error correction.

Stuart Hameroff (No Team): That's why you should look at biology. It might be better.

Julio Gea-Banacloche (Chair): I'm seriously trying to bite my tongue.

Audience laughter

Julio Gea-Banacloche (Chair): Any other questions. I'm sure there must be some comments. Yes.

Michael Hoffman (University of Ulm): It's just a comment. I would like to recall why quantum mechanics have been invented. They have been invented because experiments were done that could not possibly be explained by classical models. So, I'm waiting for the experiment that you are doing that cannot possibly be explained by classical models, and now we should do another one.

Paul Davies (No Team): I'd like to respond to that because it's the point I was going to make, that ... everyone here seems to assume that biologists seem to have a wonderful understanding of what is going on inside a living cell, and the biologists I talk to are continually baffled. For example I spoke in my lecture about the polymerase motor. You may think the basic physical principles must be understood. Absolutely not. The people who work on that say they really haven't a clue what is going on there in terms of basic physics. Somebody made the comment, "Biologists, you know, why don't they go out and learn some physics?" Mostly, biologists don't know quantum physics so, and that doesn't mean they fully understand everything in terms of *classical* physics. That doesn't follow. They are continually troubled and do not understand most of what is going on inside a living cell, except at the level of individual molecular interactions. Once you start getting something that's complicated as the polymerase motor [they are in trouble].

Michael Hoffman (Unversity of Ulm): But have they not tried to explain it by classical models?

Paul Davies (No Team): Yes, I mean there are all sorts of hand waving models around, but the classical models aren't terribly satisfactory either. I think it's a real mystery what's going on inside a cell, and the fact that biologists say, "Well, you know, it isn't a problem" doesn't mean that physicists can just sit on the sidelines saying, "Oh, it will all be explained in terms of classical physics." I think [scientists] do *not* understand what's happening. There are lots of mysteries and we do need experiments. It seems to me an entirely open question as to whether these experiments will reveal that quantum mechanics is going to be really essential for understanding some of these molecular biological properties—at least at the level of smaller components.

Sergey Bezurkov (Yes Team): I would like to disagree with Paul and support Michael. From my point of view, it depends on what you call "experiment." We probably do not actually understand what is going on in a single cell. Absolutely, I am with Paul [in this respect]. But the moment you do your experiments properly, the moment you dissect the cells into the parts that you can study with a real control over the [experimental] parameters, they [the parts] are 'golden' [i.e. can be described by laws of physics]. So, [here] I'm with Michael.

Stuart Hameroff (No Team): Can I respond to that? I think what you just said, Sergey, is that if you cut the cell up into small enough pieces, eventually you get an experiment you can perform.

Sergey Bezrukov (Yes Team): Absolutely, but I'm not ashamed by the lack of understanding [of complex biological systems]; this is where we are now, with our physics, and I am not talking only about Building 5 at the NIH, [I am talking about] everybody here and in the world.

Stuart Hameroff (No Team): So when you reduce it too much you throw away the baby with the bathwater, you've lost the essential feature of life. And the other thing is consciousness is completely unexplained by classical means.

Howard Wiseman (Yes Team): To [Stuart], about the possibility of doing the experiment: could you show one tubulin protein being in a superposition? I mean that's pretty small. It seems to me that, you know, you criticize people for saying that you can't take things apart but it would bolster your position enormously if you could demonstrate that just one protein like this could be in a superposition state. So, that's why I think, really, this isn't going forward until an experiment like that is done.

Anton Zeilinger (No Team): Suppose what I believe will come true, namely that we will find superpositions of all kinds of things including tubulin. Would that have any impact for today's debate?

Stuart Hameroff (No Team): *Addressing Wiseman and referring to Zeilinger.* He showed it for Porphyrin so why not Tubulin?

Anton Zeilinger (No Team): *Addressing Wiseman.* If so, what impact would it have on your opinion?

Howard Wiseman (Yes Team): I think it would have an impact, it would advance your side enormously. At the moment there is no evidence whatsoever that there is anything quantum going on or even *potentially* quantum going on. So, I'm not saying it would win the debate, but it would certainly do a lot for you.

Audience laughter

Howard Wiseman (Yes Team): And a comment on the difference between porphyrin and tubulin—it's enormously difficult to show a macro-molecule being in a superposition of two different configurations. That is like a miniature Schrödinger's cat. A porphyrin molecule being in a superposition in slightly different *positions*, is a completely different thing and it's much easier to do and to conceive of being true and to demonstrate experimentally.

Stuart Hameroff (No Team): The difference between the two tubulin states in our model: Professor Frauenfelder mentioned that the spatial difference in functional states is very small in a protein—is only the diameter of an atomic nucleus—so you couldn't really tell by looking at it. Of course if you looked at it you'd collapse it anyway.

Most view the brain as a hundred billion neurons with synapses acting as simple switches making up a computer. But if you look at one cell organism like the paramecium, it swims around and finds food, it avoids predators and obstacles. If it gets sucked up into a capillary tube, it gets out faster and faster each time—it can learn! It finds a mate and has sex. [Paramecium] doesn't have any synapses to process information, [but does so] very efficiently using its microtubules. If you try to develop a machine to do that, you would need a hundred million dollars.

Paul Davies (No Team): And a sense of humour?

Audience laughter

Stuart Hameroff (No Team): I'd like to think so!

Juan Parrondo (Universidad Complutense): We know that life [forms] prefer to live at a relatively high temperature, say around 300 Kelvin. If there would be quantum effects in biological processes, wouldn't there be [a preference for] life to develop at a colder temperature? Is it possible to say something *general* about this?

Stuart Hameroff (No Team): Biology has apparently adapted to utilize heat to promote rather than destroy quantum states, somewhat like a laser pumps quantum coherence. For example increased temperature enhances the quantum [spin] transfer through benzene, a perfect example of an organic molecule [found in protein hydrophobic pockets], so there must be some [kind of] electronic resonance that harnesses heat to promote quantum [processes].

Julio Gea-Banacloche (Chair): Well, it is probably about time to begin winding down. I think I would like to informally pose the question to the audience. Basically, I'm not sure that I can pose the question in a way that everybody here will approve of, so I'm not going to try. Let me just say by every individual's definition of trivial then, how many here—we can have a show of hands—would think that it's possible that there may be non-trivial quantum effects in biology, [that is], they tend to believe that there really may be non-trivial [quantum] effects in biology?

A little under 50% of the audience raise their hands

Julio Gea-Banacloche (Chair): OK. Now, how many would tend to believe that there are really no non-trivial quantum effects in biology?

A little over 50% of the audience raise their hands

Julio Gea-Banacloche (Chair): What do you say? I think there are probably more on the non-trivial side... I mean the trivial side—sorry!

Audience laughter

Derek Abbott (No Team): I'd like to see a show of hands whether people think it's worth going out and doing some experiments to check the relationship between quantum mechanics and biology. Hands up who thinks that's worth doing.

Julio Gea-Banacloche (Chair): It's a fair question.

>70% of the audience raise their hands

Derek Abbott (No Team): Hands up if you think you'd be wasting your time.

No hands are raised

Derek Abbott (No Team) Ah, nobody!

Then slowly one hand is raised—that of Laszlo Kish. Audience laughter

Julio-Gea Banacloche: Well, I would like to thank you all again and the participants for taking part in this debate. Thank you.

Audience applause

End of transcript.

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