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DOES QUANTUM MECHANICS EXCLUDE LIFE?

Peter Fong

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Does Quantum Mechanics Exclude Life?

Wigner[1] has concluded that quantum mechanics predicts a practically nil probability for the existence of states corresponding to auto-duplication of a part of a system. Therefore he suggested that either present quantum mechanics does not provide a complete explanation of all natural phenomena, including life that is self-duplicating, or it should at least be modified by including concepts such as consciousness that are not needed in describing physical phenomena. Landsberg[2], using less restrictive statistical assumptions than Wigner, found that spontaneous generation of life and reproduction are not completely ruled out by quantum mechanics, although their probabilities on the average remain extremely small.

The important point these authors disregarded is that life, or most of the present forms of life on earth, is not a self-replicating system as they conceived, as far as the mechanism of reproduction is concerned. The basic act of reproduction is the replication of DNA, the mechanism of which, according to Watson and Crick[3] and confirmed by many experiments afterwards, may be phrased by saying that DNA is actually a composite of two quantum mechanical systems A and B (the two strands) and the reproduction process involves the creation of a new B out of the substrates of the nutrient medium under the interaction of A and the creation of a new A under the interaction of B; it is not self-replicating but rather mutual-producing. The fact that life appears to be self-reproducing is due to the incidental fact that the system created under the action of A (or B) happens to be identical with the partner of A (or B) in the composite system. We now consider the consequence of the quantum mechanical considerations of these authors under the circumstances of mutual production.

Let the probability of A's producing A be denoted by p(A;A) which, according to these authors, is an infinitesimal ε. We now consider the probability of A's producing A through an intermediary B (A produces B; B then produces A). As far as the construction of a quantum mechanical system that exhibits reproduction (of A) is concerned, B is left arbitrary. Thus the probability is a sum over infinitely many choices of B,

$$p(A;B;A) = \sum_{B} p(A;B)\ p(B;A)$$

If one accepts the argument of the previous authors, one is led to conclude that both p(A;B) and p(B;A) are infinitesimals of the same order ε. Thus the above summation has the order of magnitude $\sum^{\infty} \varepsilon^2$, which is likely to be an infinitesimal.

However, the Watson-Crick mechanism of replication involves a specific kind of interaction, namely, complementary pairing or templating. This mechanism is known to occur to <u>some</u> molecular system. Furthermore, the templating mechanism is mutual (if A templates B' then B' templates A) so that p(A;B') and p(B';A) are of the same order of magnitude and are close to unity when the templating mechanism works. If A is such a molecular system, we can make the statistical treatment more specific by introducing the known fact of templating and the above summation may be evaluated as follows:

$$\begin{aligned} p(A;B;A) &= \sum_{B} p(A;B)\ p(B;A) \\ &> p(A;B')\ p(B';A) \quad \text{(A and B' template each other)} \\ &= 0(1)\ 0(1) \\ &= 0(1) \end{aligned}$$

The probability of occurrence of a self-reproducing system thus becomes finite and close to unity. Thus reproduction is allowed in quantum mechanics, not for all systems A, but for some of them.

The crucial point in the argument is that by reproducing A through an intermediary B, one is given a variety of choices of B, one of which may give rise to high probability p(A;B). In the direct reproduction process, this freedom of choice does not exist; furthermore we do not know of any known mechanism that leads directly from A to A even in special cases of A. The significance of the templating mechanism is that the probability p(B';A) is of the same order of magnitude of p(A;B') so that the final result is finite. Other mechanism may give rise to a large p(A;B") but p(B";A) may still be infinitesimal and the final result may still be infinitesimal. Thus, by introducing a specific interaction, namely, the templating mechanism, and the special device of mutual producing, life becomes possible in spite of the quantum mechanical limitation of auto-duplication propounded by the previous authors. Since templating is a very special interaction, life is not a general phenomenon of chemistry but restricted to some special molecules (DNA).

The advantage of reproduction through an intermediary, in particular, through a template, is obvious in common sense. The simplest way to reproduce a photograph is to make a negative first, and then to make a negative print of it. Many reproducing processes involve some kind of negative (a mould, for example). Actually the principle underlying the advantage of using a negative is not basically different from what we have discussed above. It is therefore no surprise that life does not reproduce directly but does reproduce indirectly by the template mechanism.

The new degree of freedom thus obtained deserves further investigation and the following is an attempt to exploit it systematically. We avoid the definition of life for the moment, which is really not necessary or useful here. Since the property of reproduction is one of the most outstanding characteristics of life we first study the general properties of reproducing systems. For mathematical convenience we concern ourselves with the study of exponentially multiplying systems defined as a quantum mechanical system (a molecule or an aggregate of molecules), the number of copies of which increases exponentially (or nearly exponentially) in time at the expense of an infinite nutrient medium in which they interact.

Many examples of exponentially multiplying systems may be cited, and no attempt is made to describe them exhaustively. One in astrophysics is the nuclei undergoing nuclear transformation by the r-process[4] (neutron capture on a fast time scale interspersed with beta-decay) eventually interrupted and repeated by the fission process. Assuming an infinite supply of neutrons (nutrient medium), the number of nuclei undergoing transformation doubles after each fission process and increases exponentially in time. The example has been mentioned by Ageno[5] in an argument against Wigner and Landsberg (in terms of neutrons instead of nuclei). The occurrence of this exception to Wigner's and Landsberg's arguments seems due to the inadequacy of the statistical treatment which left out the results of some peculiar Hamiltonian systems (the template mechanism is another example). Since the presently known life is based on reactions in organic chemistry we limit ourselves to the special case of exponentially multiplying systems based on catalytic synthetic reactions in chemistry.

Catalytic synthetic chemical reactions are well known in which a catalytic molecule by interaction causes the synthesis of a product P out of a set of reactants R, but the rate of increase of the number of the product molecules in time is linear, not exponential. However, an exponentially multiplying system of P's may be constructed by the following set of reactions with the same reaction rates:

$$R's \xrightarrow{P_1} P_2$$
$$R's \xrightarrow{P_2} P_3$$
$$\cdots\cdots\cdots\cdots$$
$$R's \xrightarrow{P_i} P_{i+1}$$
$$\cdots\cdots\cdots\cdots$$

In other words, each product is the catalyst for the next reaction in the sequence. Such a system calls for the existence of infinitely many reactions with the product of each reaction catalysing the next reaction, the probability of constructing such a set must be rather small. On the other hand, if one of the product P_{i+1} happens to be identical with the first catalyst P_1, then the exponentially multiplying system may be constructed with only a finite number i of reactions and a finite number i of catalysts, and the probability of constructing such a system would be much higher. The probability will be highest when i is smallest, i.e., equal to one; this corresponds to the autocatalytic self-duplicating system of one reaction and one catalyst. The next highest is when i equals two; this corresponds to a two-component mutual-producing system of two reactions and two catalysts, etc. The present form of life based on DNA is a modified form of the two-component system just discussed, the modification being that each generation is a composite of the two catalysts (the two strands of DNA) so that all generations appear to be the same.

It should be mentioned that exponentially multiplying system is not identical with life. But the additional attributes such as transcription (growth) that make an exponentially multiplying system a living system (whatever definition of life may be) are separate problems and should be discussed separately from the quantum mechanical problem of replication. Such discussions have been made[6] and will be published in more detailed form.

We now consider the probability of occurrence of the other exponentially multiplying system with $i > 2$. For the three-component system in which A produces B, B produces C, and C produces A, the general statistical argument would lead to a probability of

$$p(A;B;C;A) = \sum_{B}\sum_{C} p(A;B)\, p(B;C)\, p(C;A)$$
$$= \sum^{\infty}\sum^{\infty} \varepsilon^3$$

which again is likely to be an infinitesimal. On the other hand, in the special case when templating mechanism operates such that A templates B, B templates C (in addition to templating A), and C templates A (in addition to templating B), the probability may become finite. That B templates both C and A may be achieved by the geometrical and bonding configurations of two sides of the molecule B for templating C and A respectively. Yet, comparing the probability of occurrence of the three-component system with the two-component system, we find the former depending on the existence of three mutually templating molecules A, B, and C, which is less probable than that of two mutually templating molecules for the two-component system. Thus we may say that the probability of occurrence of the i-th exponentially multiplying system decreases monotonically as i increases. Hence the two-component system may be called the allowed system and the three-component system may be called the first forbidden system, etc., according to the spectroscopic custom. That life on earth belongs to the allowed system instead of the forbidden systems or the improbable auto-catalytic system is in consonant with the statistical considerations. That there is only one kind of two-component system on earth, namely, the DNA system, seems to suggest that life is a highly special and rare case in chemistry.

It would be interesting to speculate the properties of "life" based on the three-component system. The genetic molecule of such an organism would be a three-standed macromolecule with side groups of the three chains paired up in a three-way fit. If the author's theory of replication[7] is correct there is the possibility that the three-way pairing will provide a three-way check in replication and thus will improve the error rate in replication in the same way and by the same factor (10^3-10^4) as the two-way check in DNA replication improves the error rate over single strand DNA replication.[8] The lower rate of error in replication (higher quality control) would confer the organism advantages over DNA organisms just the same way as DNA organisms over the single-stranded nucleic-acid viruses. There is a possibility that the three-component-system organisms may be thousands of times more complex and presumably more intelligent than ours. While the three-component system has a smaller probability of occurrence than the two-component system, the number of hospitable planets in the universe is sufficiently large to make their occurrence not impossible.

We have argued for the occurrence of life on the most pessimistic starting point, based on Wigner's and Landsberg's conclusion that $p(P_1;P_1)$ is very small. Actually this conclusion is open to question from the following two considerations: First, life, as far as replication is concerned, is not a very complex system; it is not the whole individual but merely the genetic molecule. The complexity is reduced further by the fact that much of the complexity is in the subunits of the genetic molecule (mononucleotides) which already existed in the substrates of the nutrient medium; the act of replication is a simple process of polymerization. Second, in replication the products do not have to be exactly the same as the original and this would increase the amount of phase volume involved tremendously. It is known that a gene may suffer many changes of base sequence without showing up phenotypically, because the protein it codes has its activity dependent only on a few small areas of the protein molecule, the rest being merely space filler and may be altered without affecting the function of the protein. Thus the DNA is a quantum mechanical system which has many living states but only a few dead states (lethal mutations). In this light Wigner's and Landsberg's criticism[9] against Ageno is open to question. Altogether Wigner's and Landsberg's estimates may be unnecessarily pessimistic and the actual probability for the occurrence of life may even be higher.

It may thus be concluded that Wigner's and Landsberg's arguments exclude the appearance of auto-catalytic synthetic exponentially multiplying system[10] but do not exclude the appearance of life in the form of many-component exponentially multiplying system. The occurrence of life is the result of a tour de force (mutual producing) and an accident (properties of DNA), which are beyond the statistical considerations of the previous authors. No generalization of quantum mechanics is needed nor the introduction of new concepts beyond those of physics is required to explain the phenomena of life. As far as replication is concerned, the phenomenon is understandable from the laws of chemistry which is based on the laws of quantum mechanics and thermodynamics. As to the more general problem of life, a theory trying to understand it from the first principles of physics has been reported[6] and a more detailed sketch will be published soon.

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[1]Wigner, E. P., The Logic of Personal Knowledge, Essays Presented to Michael Polanyi (Routledge and Kegan Paul, London, 1961).

[2]Landsberg, P. T., Nature, 203, 928 (1964).

[3]Watson, J. D., and Crick, F. H. C., Nature, 171, 737, 964 (1953).

[4]See, for example, Fong, P., Phys. Rev., 120, 1388 (1960).

[5]Ageno, M., Nature, 205, 1306 (1965).

[6]Fong, P., Bull. Am. Phys. Soc., 11, 373 (1966).

[7]Fong, P., Proc. Nat. Acad. Sci., 52, 641 (1964).

[8]Fong, P., to be published; Kubitschek and Henderson, T. R., Proc. Nat. Acad. Sci., 55, 512 (1966).

[9]Wigner, E. P., and Landsberg, P. T., Nature, 205, 1307 (1965).

[10]Auto-catalytic reactions which are not synthetic in nature do occur and contribute to the existence of exponentially multiplying systems. The author is indebted to Professor Melvin Calvin for pointing out such examples as the following one:

$$\frac{1}{2} H_2 + Cu^{++} \xrightarrow{Cu^+} H^+ + Cu^+.$$