

**Quantum Uncertainty
and
The Response of the Universe**

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Quantum Uncertainty and the Response of the Universe

JAYANT V. NARLIKAR

Introduction

At the outset I wish to express my apologies to the non-scientists present at this symposium. My discussion will inevitably draw upon several basic concepts in fundamental physics which I shall try to express in a simple and nontechnical format. However, there still might remain a gap in the understanding of what I wish to convey. In an interdisciplinary meeting like this such a situation cannot be avoided. Yet, it is also an advantage to have the reactions from experts outside one's own field since they may bring some fresh inputs that have been missed by workers in the field.

I wish to describe in this talk an idea which evolved out of my joint work with Fred Hoyle. As cosmologists we were (- and still are!) concerned with the large scale structure of the universe. As scientists, we wanted to find out ways of testing hypotheses that describe the state of the universe over large scales both in space and time. One way of testing these theories is by observations of the remote corners of the universe. This procedure has the advantage of directness and the limitation of increasing uncertainty as we try to probe more and more remote regions.

The second method investigates possible long range interactions that link the large scale structure of the universe to our local neighbourhood. If we know how the effect propagates over a long range, we can deduce the conditions prevailing in the universe over large distances simply by observing their causal effect on our local environment. Here we have to contend with the speculative nature of the long range effect but it is compensated by the ease and accuracy of observing systems under our own control and in our own vicinity.

It is this second approach that I shall adopt with a view to exploring its impact on our understanding microscopic phenomena that fall within the purview of quantum theory. The title of the present symposium contains the words 'chance' and 'determinism' that have special implications in quantum mechanics. I shall begin by outlining the problem as seen in the conventional view of the quantum world. I shall then bring in the fresh inputs from long range interactions and cosmology.

From Bohr to Bell

The classical mechanics of Newton, Lagrange and Hamilton is fully deterministic. Given the initial values of certain dynamical variables which specify a system, the equations of motion determine their values in the future. Thus it is possible to predict 'what the system will do' in the course of time.

Although Einstein modified the Newtonian concepts of space and time in a radical way, he still subscribed to the deterministic nature of Newtonian mechanics and of physics in general. The advent of quantum mechanics with its inherent uncertainty and probabilistic interpretation were never liked or accepted by Einstein, although he himself made important contributions to such quantum phenomena as the photoelectric effect and the rates of atomic transitions. His dialogue and correspondence with Niels Bohr highlight the unbridgable gap in their perception of the microworld.¹

Take the uncertainty principle, for example. The position and the momentum of an electron are supposed (under Bohr's point of view) to be 'complementary variables' whose values cannot be measured simultaneously and with infinite accuracy. Now, it is expected in any experiment that these perfect conditions are never realized. Every method of measurement will be bound to have some errors. Even Newtonian mechanics allows for that. However, Newtonian mechanics does not forbid a thought experiment that attains the above perfection. Indeed, the whole facade of classical physics is based on this premise.

In the example of the electron, if we wish to work out its future trajectory, we must solve the Newtonian equation:

$$\text{mass} \times \text{acceleration} = \text{force}, \quad (\text{A})$$

together with the condition that we know *both* the position and the momentum of the electron at the initial instant, *exactly*. This is not allowed by quantum mechanics a-la-Bohr. Even in a thought experiment we cannot assume exact knowledge of the position and momentum of the electron. If we denote the position by a variable x and the momentum by another variable p , then any measurement will be subject to an uncertainty Δx in x and Δp in p such that

$$\Delta x \cdot \Delta p > h \quad (\text{B})$$

Here h is a fundamental constant of nature (= the so called Planck's constant divided by 2π). Thus we cannot achieve the idealization $\Delta x=0$, $\Delta p=0$ even in a thought experiment.

This is the Heisenberg principle of uncertainty. The quantum mechanics is adapted to take note of this limitation on determinism. Instead of being 'certain' that the electron will be at a specific position $x=x_0$ at given time $t=t_0$, we can at best attach a 'probability amplitude' $\psi(x_0, t_0)$ that it will be at x_0 . The square of the modulus of ψ for a particular position tells us the probability that the electron will be found at that location. Instead of Newton's equation (A) we have a 'wave equation' for ψ , called the Schrödinger's equation.

Thus if the electron is moving under the electrical attraction of the atomic nucleus, Schrödinger's equation will help us determine the various probabilities of the different states in which the electron could exist. We can do no more than that. By contrast, Newtonian mechanics would have determined the orbit of the electron precisely.

¹ *The Bohr-Einstein Letters*, New York 1971.

In actuality, experiments seem to favour the Schrodinger picture rather than the Newtonian picture. Does this mean that the latter is totally wrong? Or is it incomplete? Einstein and several other scientists felt that the latter alternative deserves to be considered further. And so the idea of 'hidden variables' was mooted.

The hidden variables are basically new variables, in addition to the manifest variables of Newtonian mechanics. Thus in the case of the electron we cannot decisively predict its future trajectory because we do not know the values of these extra variables and how they come into the traditional Newtonian equations of motion. Had we known them we could have been as deterministic as required by Newtonian mechanics.

Notice that in the hidden variables theory (HVT) the lack of determinism is not inherent but is due to a lack of knowledge about all the variables specifying the system. Thus the basic philosophy is the same as Newton's, i.e., deterministic.

In the thirties there were discussions on the HVT and several thought experiments like the Einstein-Podolsky-Rosen paradox were discussed.² However, the possibility of deciding between quantum mechanics and the HVT by experiments became real with the important contribution by Bell. Bell in 1964 derived an inequality on the assumption of a local HVT, an inequality that could be tested in a real experiment.³ Subsequently experiments have been performed to settle the issue and they have ruled against the local HVT, and in favour of quantum mechanics.⁴

However, the debate has not ended!

Long Range Interactions

Bell's inequality was derived and tested for the *local* hidden variable theory, that is, where the extra variables are confined to the actual location of the microsystem. It still leaves open the possibility that the hidden variables are *non-local*, i.e. not confined to the immediate neighbourhood of the system being observed.

The proposal I wish to discuss today relates to non-local interactions between the observed microsystem and the universe at large. This idea may appear mysterious but can be made into a proper physical theory as I intend to show next.

To begin with consider our example of the electron in an atom, say the hydrogen atom. Observations show that the electron can make transitions between the so-called stationary states. Quantum theory tells us that in a stationary state the total energy of the electron stays constant as it moves around the nucleus. However, the energy values cannot be arbitrary. They form a discrete set, with a minimum value. The electron can change over from one stationary

² A. Einstein, A. Podolsky and N. Rosen, *Phys. Rev.* 47 (1935), p. 777.

³ J.S. Bell, *Rev. Mod. Phys.* 38 (1966), p. 447.

⁴ J.G. Cramer, *Rev. Mod. Phys.* 58 (1986), p. 647. See also A. Aspect, a., J. Dalibard, G. Roger, *Phys. Rev. Letters*, 49 (1982), pp. 49, 1804.

state to another whenever it is 'induced' to do so by ambient radiation. Thus if it has initial energy E_1 , then it can 'jump up' to a state of higher energy E_2 provided the radiation can supply the quantum of energy difference $E_2 - E_1$. Likewise, in the presence of such quanta (of energy $E_2 - E_1$) in the radiation the electron can also 'jump down' from the higher energy state to the lower energy state. In this case it emits a quantum of radiation of energy $E_2 - E_1$.

It was Einstein who first calculated the upward and downward transition probabilities under such induced transitions. The probabilities are equal, Nevertheless the electron 'prefers' the state of lower energy ... it has an additional mode of downward transition that is spontaneous, i.e., not manifestly related to the intensity of ambient radiation.

This 'spontaneous transition' has been something of a mystery to me. It appears that an electron in a higher energy state decides to jump down without any external inducement. Why does it happen? In the quantum theory of radiation it is argued that even in the vacuum state of radiation, there is a non-trivial activity going on and it is this that causes the electron to jump down apparently spontaneously.

The text books on quantum field theory describe the above effect through a mathematical formalism of 'creation' and 'annihilation' operators. It works in the sense of giving the right answer for the probability of spontaneous transition. All the same, as mentioned before, one has to invoke nontrivial properties for the vacuum state of radiation. I will not go into the details of how it is done and the contortions needed to get round unphysical infinite results that crop up now and then.

The alternative I wish to describe invokes the concept of the 'response of the universe' - a concept in which the whole universe is in constant interaction with the atomic electron and whose reaction or response not only triggers but is triggered off by the downward jump of the electron.

But how is this cosmic interaction set up?

The Wheeler-Feynman Theory

How can an electron make the entire universe dance to its tune? The mechanism involves the concept of action at a distance that was used by Newton in his law of gravitation and later by Coulomb in his law of electrostatic attraction or repulsion.

In Coulomb's law, for example, two electrons repel each other by a force that acts across the space separating them. Moreover, it acts instantaneously! That is, no matter how far the electron A is from electron B, the influence between them is felt by each instantly.

This notion of instantaneous action at a distance is somewhat unrealistic, as the experiments in electricity and magnetism began to show. It became clear during the nineteenth century that the force between moving electrons was not entirely accounted for by Coulomb's law. The mathematician and physicist, Gauss wrote to his colleague Weber in 1845:

I would doubtless have published my researches long ago were it not that, at the time I gave them up, I had failed to find what I regarded as the keystone, *Nil actum reputans si quid superesset agendum*: namely, the derivation of the additional forces – to be added to the interaction of electrical charges at rest, when they are both in motion – from an action which is propagated not instantaneously but in time, as is the case with light.

Thus Gauss had intuitively guessed that electromagnetic effects propagate not instantaneously but with the speed of light. However, he did not back his intuition with a mathematical formalism (which he could have done had he put his mind to it!).

In the 1860s, the task was achieved by Maxwell in another fashion. Following Faraday's idea of a 'field' Maxwell regarded the electromagnetic field as an entity in itself, existing side by side with electric charges. Thus when electron A moves, it produces ripples in the electromagnetic field. These ripples spread outwards with the speed of light until one such wave hits electron B, making it move. In this way B feels the effect of A not instantaneously but after the duration a light ray takes to move from A to B. This idea of a field became accepted because it explained several phenomena of electromagnetic nature including the additional effects referred to by Gauss.

However, Gauss's own suggested concept of direct but delayed action at a distance was taken up by several scientists in this century. Thus Schwarzschild, Tetrode and Fokker formulated the concept in a mathematical form.⁵ I will not go into technical details here, but will highlight one strange consequence of the theory.

Being a dynamical theory, it had to obey Newton's third law of motion, viz: 'every action involves an equal and opposite reaction!' Imagine its consequence for the two electrons A and B. To fix ideas, let us assume that they are 1 light hour apart. This means that any influence from A gets to B in one hour.

Suppose we shake electron A at 4 p.m. It will produce a jitter on B at 5 p.m. What will be the reaction of B on A? It will be equal and opposite not only in space, but also in time! In other words, B's reactionary force will leave B at 5 p.m. and reach A at 4 p.m.

This 'backward-in-time' propagation of signals seemed an obvious drawback of the entire theory. Supposedly acausal, the theory was in conflict with our everyday experience. Or was it?

The issue was resolved by J.A. Wheeler and R.P. Feynman in 1945 when they brought the whole universe into consideration.⁶ In our example of electric charges A and B, their mutual separation is immaterial: A gets the reaction from B at 4 p.m., at the same instant when its initial motion took place. Even if B were thousands of light years away, its reaction would be felt by A instantly.

⁵ Respectively, K. Schwarzschild, *Gottinger Nachrichten*, 128 (1903), p. 132; H. Tetrode, *Zeits. F. Physik*, 10 (1922), p. 317, and A.D. Fokker, *Zeits. F. Physik*, 58 (1929), p. 386; *Physica* 9 (1929), p. 33 and *Physica*, 12 (1932), p. 145.

⁶ J.A. Wheeler and R.P. Feynman, *Rev. Mod. Phys.* 17E (1945), p. 156.

So, argued Wheeler and Feynman, we should include all electric charges present in the universe to calculate the total reaction to A's motion at 4 p.m. The calculation, when they performed it, was not difficult but it had a startling conclusion. The total response from the universe had such inbuilt interference that it cancelled out all backward-in-time signals in the neighbourhood of A!

Thus, if we just had a pair of electrons around, we might have noticed acausal effects. With the whole universe responding at once to the electron A, these effects disappear. We are left only with those effects which move forward in time. This crucial outcome is due to the property of the universe that it completely absorbs all electromagnetic signals originating, anywhere within it. The universe, in the language used by Wheeler and Feynman is a 'perfect absorber'.

In other words, there is no manifest discordance with observations, provided we live in a perfectly absorbing universe.

The Expanding Universe

Although they thought that they had solved the causality problem completely, Wheeler and Feynman had omitted to take one important detail into account. They had assumed that the universe is static when in fact it is expanding.

In an expanding universe, the main conglomerations of matter, the galaxies, are moving away from one another as if the entire space in which they are embedded is expanding. This has a major consequence so far as time arrow is concerned. The changing state of the universe provides an arrow of time with respect to which the 'forward-in-time' and 'backward-in-time' propagations of signals can be measured. Thus a universe which is a perfect absorber in the future may not have been so in the past or vice versa. In a static universe there is no absolute arrow of time and so Wheeler and Feynman's work had basically remained incomplete in the following way.

A static universe is perfectly absorbing both in the past and the future. As such, the Wheeler-Feynman theory cannot attach an absolute significance to signal propagation either forward or backward in time. To emphasize the distinction between the two modes of propagation they were forced to bring in the thermodynamic arrow of time. Later work, however, showed that the recourse to thermodynamics was unnecessary.

Their calculations could be performed in the well known expanding models of the universe which supply the distinguishing arrow of time. First J.E. Hogarth and later Fred Hoyle and I were able to demonstrate that in most big bang models of the universe the electromagnetic signals travel the wrong way, i.e., in the past direction.⁷ However, the steady state model of the universe generates the correct response. In this universe the electrical signals move forward in time.

The crucial feature turns out to be 'perfect absorption'. A universe (like the steady state one) can generate only forward-in-time signals provided it is a per-

⁷ See J.A. Hogarth, *Proc. Rog. Soc.*, London, A. 267 (1962), p. 365; F. Hoyle and J.V. Narlikar, *Proc. Rog. Soc.*, London, A. 277 (1963), p. 1

fect absorber in the future but not in the past. The ever expanding big bang models are of the opposite type: they are perfect absorbers in the past but not in the future.

The Quantum Universe

The work of Wheeler and Feynman was entirely classical – with no quantum mechanical implications. Hoyle and I went further to see whether their work could be extended to describe the quantum theory of electromagnetic interactions. We were able to demonstrate that it can.⁸ And we found that the response of the universe provides the missing link I mentioned in connection with atomic transitions.

Thus when an electron is in a state of higher energy E_2 it has three options open: (i) to stay in the same state, (ii) to jump down to a state of lower energy E_1 , or (iii) to jump up to a state of higher energy E_3 .

Quantum mechanics requires us to explore each possibility. It turns out that the response of the universe rules out (iii) and provides a unique probability per unit time that the electron will adopt course (ii).

Notice that the calculation proceeds in logically self-consistent loops. One loop is that the electron stays put, in which case there is no movement and no response from the universe to 'push' the electron down. The second loop involves a 'jump down' scenario. As the electron jumps down it radiates and evokes a response from the universe. It was this response that provided the push for the initial jump down. Thus there is no absolute distinction between cause and effect. Both the jump-down and the response are causes and effects of each other. The third case of 'jump up' is ruled out for the lack of a similar logical loop of reasoning. This probabilistic nature of what will happen is due to quantum theory.

In the course of our work we discovered that the quantum response of the universe always plays a crucial role in deciding the microscopic behaviour of electromagnetic systems. Indeed, it has been something of a mystery that although electromagnetic interactions are time symmetric (i.e. make no distinction between the past and the future) there are unidirectional phenomena like radiation, downward spontaneous transitions, etc. The reason, as seen in the cosmological application of the Wheeler-Feynman theory, lies in the quantum response of the universe – provided we live in the right kind of universe!

Let us now generalize this concept.

The Universe as a Hidden Variable

In a local laboratory experiment of a microsystem the quantum uncertainty is an unavoidable outcome. Is it due to a fundamental limitation imposed by nature, as Bohr believed? Or, are we missing something in a purely classical picture that leads us to the lack of determinism – as Einstein hoped to

⁸ See F. Hoyle, and J.V. Narlikar, *Ann. Phys.*, N.Y. 1969, 54 (1969), p. 207; F. Hoyle and J.V. Narlikar, *Ann. Phys.*, N.Y. 62 (1971), p. 44.

demonstrate? As to the latter question the local HVT already seems to be ruled out.

However, the example of how the Wheeler-Feynman theory works, already holds out a possibility that has not been explored fully: namely that *no laboratory system, howsoever small, is isolated*. We may claim to know all the dynamical variables related to the system per se, but we may be wrong in believing it isolated. The 'response' of the universe may very well enter and alter the outcome. And the response may allow for several outcomes to a local experiment, because each outcome represents a self consistent logical loop.

If we knew all the details of the response, we could perhaps predict the outcome in a deterministic way. The fact that the response of the universe in an integrated effect prevents us from doing that. This is where the lack of determinism comes in.

In this sense the universe is a collection of non-local hidden variables. The 'fundamental' limit of equation (B) should in principle be derivable from the large scale structure of the universe. Thus a more complete theory is needed to link the cosmological aspects to the local microsystem.