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MacLeod, Christopher

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The Known, Unknown and the Incalculable in Quantum Mechanics – and its Repercussions for Travel to the Stars

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Christopher MacLeod

Abstract

This article outlines a view of the quantum mechanical wave-function as the limit of classical mechanics. It argues that the region inside the wave-function is physically unrelated to that outside and represents a fundamentally different reality. A review of published evidence for this view is presented and it is argued that these ideas (and indeed more traditional physics and mathematics, even if the interpretation is incorrect) lead logically to the possibility of interstellar travel and teleportation through quantum mechanisms. Some of the practical implications of this are also explored.

Keywords: Quantum Mechanics, interstellar travel, propulsion, teleportation, relativity, space travel, physics

Introduction

There are still many mysteries at the edge of physics. However, the pillars of the modern subject have been in place for more than a century and most scientists feel that they have good grip on them. But what if they are wrong - what if the accepted interpretation of reality is based on a misinterpretation of the data? This article argues that this is indeed the case. Furthermore, the accepted interpretation is leading us up blind alleys and the alternative opens the way to travel between the stars.

It is now more than eleven decades since Max Planck delivered his famous paper on black-body radiation and with it heralded the arrival of a new scientific discipline - Quantum Mechanics. This has since become one of the two pillars of Modern Physics – the other being Einstein's relativity. Physics today is effectively split into three areas: Classical Physics – the laws of the everyday, which we all learn at school and on which much of engineering and technology is based; Relativity – which governs objects moving at speeds near that of light and in other similarly extreme situations; and finally Quantum Physics – descended from Planck's paper and which generally describes the behaviour of very small objects like atoms and molecules. In fact, relativistic physics is really just a logical extension of the classical kind – but the quantum theory is something totally different all together.

Most people with an interest in science are familiar with the strange predictions of quantum mechanics – cats which are neither alive nor dead, particles which can teleport across space and the potential for super-fast computing. However, these, fascinating though they are, are not what this article is about – it's about looking at quantum theory in a totally different way – as a limit to classical physics and an opportunity to travel to the stars. This view is different from the conventional one, but it fits the observed data equally well.

The meaning of the wave-function

Let us start our journey by considering one of the fundamental features of quantum mechanics – the so-called “wave-function” or “wave-packet.” This is an idea which stems from the fact that there are limits in the precision to which we can know the position and momentum of a particle – a concept which is one of the key principles of the theory and is usually called the “Heisenberg Uncertainty Principle.” The extent of this uncertainty is expressed mathematically by the wave-function. You might picture this as a flexible travelling bubble^a, which can expand, contract or change its shape, depending on the environment surrounding it. When we look for the particle, it will be found somewhere inside the bubble – but we cannot predict exactly where – only the probability of finding it at a particular place – which is related to the diameter of the bubble at that spot. If the bubble is well confined in space, the wave-function is sometimes called a wave-packet. The particle only appears to be at an exact location when it interacts with the surrounding environment and gives its presence away (at least to some extent) – in the terminology of quantum mechanics we say that wave-function “collapses.” It is important to understand that the wave-packet (and therefore the uncertainty in the particle's dynamics) has nothing to do with the precision of the equipment being used or the skill of the observer – it is a fundamental fact of nature.

Let us think for a moment about how this state of affairs may be interpreted. We know nothing (other than some probabilities) about where the particle is inside the wave-packet – if it can be said to be anywhere at all (or everywhere at once)! The classical physics within the packet volume has therefore failed completely. In effect, we live in a pixelated reality, not knowing anything of the information contained at dimensions finer than the pixels. So another way of looking at the wave-packet is to say that it represents the physical variables (in terms of energy, time, momentum and place) at which a complete breakdown of classical physics occurs – where the behaviour of objects is unrelated to the outside “classical” world. It's rather like cracks in ice or holes in a sieve – and we know nothing about the nature of things beneath. Perhaps the wave-packet can even be viewed as a “gap” in the fabric of space and time, a left-over result of the processes which controlled the foundation of the universe itself. If this is so then the warping of space and time is better described by it tearing rather than bending.

The argument above is a logical assessment of the available evidence. After all, by using radically different mathematics to describe what happens inside the wave-packet, unrelated to that which describes the outside, physicists are tacitly admitting that it is a separate (and

essentially independent) system^b. It is effectively the limit of classical physics. This might explain why it is proving so difficult to unite quantum theory with the relativistic theory of gravity (which is really part of classical physics) – because they can't actually be merged, they are fundamentally not part of the same reality (and this will still be the case even if gravitons, the particles which may carry the gravitational force, are discovered).

In the 1960s John Bell published a famous theorem. In this he showed that there are no "hidden" variables at work in quantum mechanics – there is no obscure "guiding hand" which defines the particle variables inside the packet. However, Bell pitched his theorem in terms of the variables in classical space-time and not in terms of the idea above – that the wave-packet actually represents the breakdown of this (even although such a breakdown is, again, an unstated conclusion of his result). Quantum mechanics may possibly yet hide a deeper truth, but only if it is pitched into a "state-space" (a group of different variables) outside those of classical physics^c and which correspond to a deeper layer of reality. Incidentally, the system of particles with entangled spins, suggested by Einstein and his co-workers, and often used to illustrate Bell's point, is not a good example of observations made above because it is complicated by the already-linked complementary spins of the two objects.

Consequences

There is a major consequence of the idea that the wave-packet represents a region outside classical physics as described above. That consequence is this: Just as the other laws of physics do not apply within the packet, neither does special-relativity – the restriction imposed by the speed of light has no meaning inside the packet – because speed itself has no meaning. This is implicit in the mathematical rules which govern wave-packet collapse – but because the wave-packet is usually so small that it can be effectively either ignored or replaced by simple probability in calculations – and the issue is usually swept under the carpet. Some books actually try and explain it away by saying that no information may be transmitted like this – although this is a redundant argument, which only applies to objects in the relativistic domain of classical physics. In fact the rules of special-relativity are being replaced by a set of broader laws, which govern information transmission statistically.

There are several lines of good experimental evidence to support the contention that simple special-relativity is violated inside the wave-packet. These effects are not obvious because the volumes involved are usually very small and difficult to study at normal energies. One area where such behavior is observed is in Quantum Tunnelling. Tunnelling is one of the most counter-intuitive consequences of quantum theory. To illustrate it, let us say that one is inside an enclosed metal cylinder with a rubber ball. In the classical world, if we throw the ball at the wall, we'd expect it to bounce back to us. However, in the quantum world, the ball will occasionally "tunnel" through the wall and appear on the other side. This has nothing to do with it penetrating the wall in the conventional sense – like a bullet penetrating metal. Instead it is a manifestation of the uncertainty in the ball's position, as expressed by its wave-packet – and

nothing like it exists in our everyday world. Of course, to “see” tunnelling the “balls” have to be the size of atomic or subatomic particles^d and the “wall” is a potential barrier, like the barrier across the PN junction in a semiconductor diode -in fact one type of diode, called the Tunnel Diode, works in just this way.

What is particularly interesting is this: If the particle is treated as a classical entity, and it is seen to appear on one side of the barrier, just before tunnelling, the breakdown of classical physics suddenly becomes very obvious – for it then appears on the other side of the barrier instantaneously. It has apparently travelled from one side to the other faster than light¹. In fact, all that has really happened is that the wave-function collapsed on one side of the barrier (and we saw the particle), it then re-established itself and the probabilistic nature of the system manifested the particle immediately on the other side. To all intents and purposes the particle has “teleported” through the barrier. As early as the 1930s, the phenomenon was seen by L. A. MacCall² at Bell Labs, who noted: “When a particle tunnels through a barrier, it does so without appreciable delay”. Later, in the 1950s, the Nobel Prize-winning physicist Eugene Wigner and his student Leonard Eisenbud investigated it^{3,4} at Princeton. They too concluded that tunnelling particles travel faster than light. In more recent times, researchers at Berkeley⁵ have tried to find an explanation within a relativistic framework by invoking the idea that it is the wave-packet’s group velocity which transverses the barrier superluminally. It should be noted here that, although these observations were pitched in terms of particle speed, as if the particle were travelling like a classical object - it is not, and the apparent breaking of the light velocity barrier is entirely consistent with the mathematical laws of quantum mechanics. Still, it illustrates how much researchers want to make the inner workings of the quantum mechanical wave-packet reconcilable with classical physics.

Other aspects of the incompatibility of wave-packet internal dynamics with classical physics can be seen in related experiments. For example, another Nobel-laureate - Steven Chu, has investigated it in particle scattering⁶. Another closely related phenomenon is the propagation of electromagnetic fields through the decay region of a post cut-off waveguide⁷. A waveguide is a conduit through which electro-magnetic waves like radio or light can travel – in fact, a good example of one is a fibre-optic cable - which is a waveguide for light. At microwave frequencies (where most of these experiments have been done) the most common wave-guide is an actually an empty metal tube or pipe, typically made of brass or aluminium. If the tube is too small for the signal being transmitted (if the wavelength of the signal is incompatible with its aperture), then the waveguide is said to be beyond “cut-off” and the signal dies away very quickly inside. This is analogous to the behaviour of the wave-packet crossing the barrier in tunnelling and, as in the case of tunnelling, the wave appears to cross the cut-off section of the tube faster than light.

There are several other examples which demonstrate the strange nature of reality inside the wave-packet; however, one final but important one will suffice. This concerns nothing less than the origin of time. The

mystery here is that physical laws appear to be mathematically the same whether you consider time to run forwards or backwards – and therefore the sense of time having a forward direction, which we perceive, is difficult to root in the theory. The laws of physics can even be rewritten without reference to time at all, a time-less formulation sometimes termed the “block universe.” One of the main ways in which time reveals itself is through the second law of thermodynamics – this shows mathematically how disorder in an enclosed system tends to increase and therefore gives time a directional arrow. What is interesting, however, is that it has recently been shown that the second law of thermodynamics arises from a mathematical description of the wave-packet⁸, and this “crack” (or imperfection, if you prefer) in the universe is what causes the passage of time. This is surely the strongest manifestation of the effects discussed above. The reason can be seen intuitively if one considers the nature of the present. At *this time*, all those entities which are “outside” classical reality – because of their inherent uncertainty can, in the future, manifest themselves in any place. Bell showed that the lack of hidden variables in the system means that this place is not in any sense completely predictable (it is subject to the normal role of the uncertainty principle in the absolute). So the future is uncertain at all levels – it really does not exist until it happens – the arrow of time reappears in the physical world, courtesy of quantum mechanics^e.

As technology develops other aspects of the relationship between the classical and quantum worlds will become apparent – for example, what is the nature of space-time bending by particle in superposition – a distributed area of matter/energy or a point particle? This will answer Bell’s point on the nature of things once and for all.

In physical science today, much emphasis is placed on the field of particle interactions and reactions and in developing a complete theory of these. This would provide a framework which explains the nature of the forces and transformations present in the universe. It is obviously an important step on the road to understanding the nature of things. However, it means that less effort is being spent on unraveling the bizarre nature of space and time themselves (which are often just seen as the backdrop against which the particles move) and their relationship with matter (in the causal sense). Hence the comparative lack of interest in the phenomena discussed here. Many physicists prefer to ignore such philosophical consequences of their theories (sometimes called the “shut-up and calculate” attitude). However, as discussed below, once technology catches up, ignoring the true nature of things can no longer be justified.

Onwards to the stars

So, what relevance does all this have to the exploration of the universe? Before we answer that question, let’s first consider the other ideas for interstellar travel. These can be divided into two categories. The first can be classed as “conventional” methods – the engineering is within (or nearly within) our current capabilities – although most would be prohibitively expensive. Such ideas include chemical rockets, ion or plasma drives, solar or light-pressure sails and various nuclear engines. These devices accelerate a space-ship to very high speeds, so that a

journey to the stars may be accomplished in several human lifetimes – hence, many of these designs are labelled “generation ships” - since only the descendants of the original voyagers will finally reach their destination. The second class of ideas are ones which are highly speculative and usually rely on relativistic mechanics to make them work. One such idea originated with Miguel Alcubierre, a Mexican physicist, and is referred to as the Alcubierre drive. This device warps space in such a way that it allows the local speed of light limit to be violated. Unfortunately, it is somewhat doubtful whether it is physically possible to implement the drive - as it requires the generation of a negative energy-density in space, which is only achievable using hypothetical states of matter, never observed in nature, and perhaps unlikely to exist at all. So, there are interesting ideas for interstellar travel which involve both classical physics and relativistic physics – but what about quantum physics? Well these have been conspicuous by their absence.

The key to using the dynamics of the wave-function to facilitate superluminal travel lies in two facts: Firstly, the wave-packet can exist at remote places in space; and secondly, it can be “engineered” into different forms and shapes. Let’s examine each of these in turn. Although a wave-function is usually localised in space, it also has a non-zero component in remote locations. It’s not quite true to say that it exists everywhere as, in some places, its contributions can cancel themselves out completely and in others they are very small^f. In fact, in normal circumstances, interference between different parts of the wave lead to it being reduced to negligible proportions away from a relatively small region around its centre. This is why we are not normally aware of any uncertainty in a particle’s localisation^g. Never the less in other circumstances - if the experiment is engineered to show it (as in the tunnelling experiments), the fact that the wave-function has a finite value in distant regions can manifest itself as a particle appearing in a remote place. This “universal” aspect of the wave-function is clearly shown in Richard Feynman’s so-called “sum over histories” approach to quantum mechanics^h – where the correct answer to wave-packet problems is only obtained by considering the sum of *all* possible states that a particle can be in. Another interpretation of Feynman’s approach is that the particle is present (in some sense) at all locations before the wave-function collapses - and can, in the right circumstances, appear anywhereⁱ.

So, what about “engineering” the wave-function? Well, it can be manipulated - and in-fact, this is what is done in the experiments already described^j. There are two issues here. The first is about putting the particle in a position where the non-localised quantum nature of its wave-function becomes apparent (as opposed to its normal “particle-like” nature) - so it can spread and evolve according to the rules of quantum mechanics (the evolution and behaviour of the wave-function is described by the famous “Schrodinger equation”). Effectively we need to stop the wave-function collapsing; to do this, the particle must be isolated from the environment; as any interactions, even with radiation, will force it to “give the game away” and appear at a particular point. Such a situation is sometimes referred to as putting the particle into a “superposition” state. Next, the shape and evolution of the wave-function itself needs to be

manipulated - so that it extends into the region of space where we want it. This is often done by means of a "potential-well", which is effectively a prison for the particle and confines the wave-function within fixed bounds. The well can be formed by any force which confines the wave-function (for example, gravitation or the strong nuclear force) - but electro-magnetic forces are usually the easiest for scientists to manipulate in a lab^k. Inside the well, the wave-function forms distinctive topologies which are created by a combination of constructive and destructive interference and which are, in turn, the result of the well shape. Hence, the regions where the particle is most likely to appear can be manipulated and engineered.

So this is the basis of quantum travel to the stars: Put the object to be transported into superposition; engineer a long potential well - a "quantum corridor" and allow probability to manifest the object in another part of space^{l,m}. This idea based on the accepted mathematical description of the wave-function and is valid even if the speculation contained in the first part of this article on the relationship between classical and quantum physics turns out to be falseⁿ. It might seem, at first sight, that this violates causality - but actually the lack of predictability in the space-time coordinates of the object's appearance in a remote location means that causality is no more a victim than it is in any other quantum operation. The uncertainty principle puts a limit on this and the possible transfer of information using it^o - in other words the speed restriction in relativity is replaced by the probability calculations of quantum mechanics. You might call such a system a "finite improbability drive" as opposed to Douglas Adams' infinite one!

Practicalities

What are the problems with such a scheme and how these might be overcome? One issue is that, rather than a single particle, we are talking about putting large systems of interacting molecules into a superposition state. This is inherently much more difficult than for a particle. There are several possible ways around the issue. Firstly, progress has been made doing it in the lab, and some research groups have actually achieved the superposition of macroscopic objects⁹. However, it is true that, at least initially, it may be only possible with small, simple objects. Several options are also available for evoking unusual quantum states, in which a large object can appear as a single wave-function - although these usually involve extreme cooling. Two examples are super-fluidity and Bose-Einstein condensates. It may be possible, in the future, to engineer the properties of materials so that they can achieve superposition more easily or to produce a "shield" for complex items with such substances^p.

Finally, what about the obvious question - how could this be done practically? Well, one way of considering the wave-packet, mentioned previously, is that it is the values of the state-variables (like energy and momentum) where normal space-time breaks down^q. For macroscopic objects, the energy required to produce a big packet is very large. However, we are fortunate in having, at the centre of each solar system, the largest thermonuclear fusion reactors in the universe - the stars. They could potentially supply the vast resources required to achieve transport - for example, by supplying the power for energy beams which could form

the travel corridor. It may also be possible to move in a series of very small, incremental, steps – rather than large single jumps – this would be more like the common conception of a spaceship and requires much less initial energy.

Conclusions

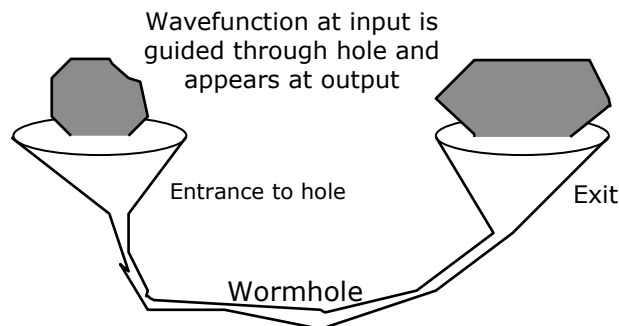
The idea that the quantum wave-function represents a strong discontinuity or breakdown of the fabric of space-time is not the conventional view. The suggestion that relativity is, in some sense, violated within its confines, is even more contentious. However, as discussed above, it is an interpretation which is just as consistent with the evidence as any of the others currently proffered - and there are several lines of independent experimental evidence to back it up. Whether it is correct is a question which can (and will) be answered using experimental methods. As far as interstellar travel is concerned, obviously this lies in our future, and the system described above are currently still beyond our technological capabilities. However, this does not mean that we shouldn't discuss it and its philosophical basis – for today's dreams are tomorrow's reality.

Further notes, thoughts and clarification (not in original article)

- a. A bubble is perhaps not a good analogy though - as the wavefunction can have a very odd shape and infinite boundaries! Another way of visualising it might be as a mist, the centre of which is concentrated and which thins (although never completely disappears) at its edges.
- b. The converse being that there is a single universal law, the outcomes of which change gently from the smallest scale to the largest, without any discontinuity as we leave the wavefunction.
- c. Which might be completely outside the construct we call “the universe.”
- d. In fact, Quantum effects and QM are not at all limited to the very small (either in theory or experiment) - they simply need more careful engineering to become apparent at larger scales. The universal pervasiveness and quantity of natural radiation is what normally limits them and their visibly - however, clever engineering can remove this barrier.
- e. The connection of the wavefunction with thermodynamics (and its limits) has major repercussions for computing and, in particular, the ability of machines to overcome the limitations on conventional computing machines explored by Turing and Godel (a topic quite distinct from “normal” quantum computing, see New Scientist, no 2978, pp. 34-37). Similar issues also apply to other “laws” or “impossibilities” in standard physics.
- f. Or, alternatively, it does exist everywhere but can cancel itself out if the circumstances are right.
- g. The so-called “Orgy of quantum interference” means that, in normal circumstances, the particle is well-confined and extra-classical behaviour can be conveniently ignored.
- h. There are actually quite a number of different formulations of Quantum Mechanics - each with a subtly different emphasis and way of looking at the QM world. Earlier incomplete versions by Bohr and others were superseded by Matrix Mechanics and the Wave Equation (which many physics courses still teach). These were complete within themselves but were later amalgamated by Dirac into the

bra-ket notation and approach (which is often preferred by mathematical physicists and more modern postgraduate courses). Later still, Feynman developed a somewhat different approach, originally aimed at the layman, in his book “QED”. This was deeply rooted in his field of Quantum Field Theory (QFT) and his own unique understanding of the subject - and there are also many other approaches. In general, one could make the case that the QFT approaches emphasise the non-local universal nature of the wavefunction more than earlier ones.

- i. It is sometimes stated that, although behaviour inside the wavefunction follows quantum rules, the function itself propagates according to the laws of relativity. To quote Born: “The motion of particles follows the laws of probability, but the probability itself propagates according to causality.” However, it is clear from the philosophy of Feynman’s (and other QED) approaches that it exists everywhere in space at all times. To quote Cox and Forshaw (The quantum universe, Penguin, 2012, p. 46): “The particle can be anywhere else... at every conceivable point in space.” This does not violate causality, according to this view, because the statistical laws of information-transfer are more fundamental than those restricting travel to the speed of light (a view echoed in the original article). We cannot predict exactly where the object or particle will appear in space and this means that it cannot be used to accurately transfer information (see p. 47 of the same book). If these two laws (relativity *outside* the packet and statistics *inside*) are indeed completely equivalent (something which has not been satisfactorily shown), then this does show some deep connection between the volumes inside and outside the packet. However, another possibility is simply that the statistics inside and the speed-limit outside are getting confused in the experimental and theoretical treatments and are not actually equivalent - but just look similar.
- j. Quantum constructs (like quantum “dots” and “wires”) operate as electronic devices from within the classical domain. A new engineering may be proposed which focuses on the interior of the wavepacket (ie, it works from the inside-out) - engineering within the quantum domain and not subject to classical laws.
- k. In the far future it may be possible to engineer potential-wells based on gravity. Either from:
 - Artificial singularities (point-like or extended).
 - Or (if they prove to be physically possible) artificial or natural worm-holes. In this case, a wavefunction present at one “mouth” of wormhole may also be present at the other - having been guided through the hole to a distant point in space.



- l. Of course the forces forming the well have to propagate at or below the speed of light (if the well is not a pre-existing natural phenomenon). However, the object to be transported does not have to be present while this is happening. This propagation of restraining forces may also be why some of the phenomenon

- discussed can appear to be move within the classical speed range. Naturally existing wells and corridors could be conduits for the wavefunction - all the matter in the universe is connected by gravitational forces (and therefore the complex topology of space-time); however, their extent and nature is sometimes poorly understood (they are essentially invisible except perhaps for their effect on surrounding matter).
- m. Perhaps leading to a new engineering area - Natural and Artificial Quantum Well Engineering.
 - n. The opposite is also true: The first part of the paper may be correct even if the second part is wrong.
 - o. Is there a hard limit to information transfer - might the amount of information transfer be statistically determined like the rest of Quantum Mechanics? There are some indications of this from experiments on weak observations (see New Scientist, no 2979, pp. 32-35).
 - p. "Shielding" could also refer to a shield against wavefunction collapse (an observer or radiation shield).
 - q. There are also repercussions of these ideas for the topic of time-travel, which I have chosen not to explore here.

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