Science Fact

Another Way to the Stars

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There are those who say that travel to the stars is little more than a pipedream—at least in practical terms. Sure, in hundreds of years it might be possible to build "generation ships," where large numbers of people labor over centuries so that their descendants might eventually reach a new world. Perhaps we'll discover the secrets of suspended animation and leave our friends behind for a long sleep. If we ever develop ships that can travel at close to relativistic speeds, itself a huge challenge, we might reach the stars in a few tens of years—but again at the cost of losing all those around us because of time dilation. One thing seems certain however—the chances of a *Star-Trek*-like "warp drive" are next to nothing; the laws of relativity put pay to that . . . don't they?

And yet there are those who dare to dream. They stretch the axioms of physics to their limits—perhaps beyond their limits. One such is Miguel Alcubierre, inventor of the eponymous drive. In 1994, he proposed an audacious machine—a vehicle that could bend the geometry of the Universe around itself and travel in a sort of enclosed spacetime bubble to produce a result akin to the idea of warp drive.

Before we get too excited about visiting Tau Ceti Four however, there's a couple of issues to note. The resulting ship would require huge energy (perhaps more than that present in the observable cosmos) and of a type that has never even been shown to exist—negative mass-energy. Since his proposal, others have refined and worked on the idea—but the results always require unverified exotic forms of matter or energy in unbelievable quantities.

And such it is with all similar ideas—in the final analysis they all need some essence beyond verified physics. In many ways such requirements are akin to magic—and like magic, they probably don't exist beyond the realms of wishful thinking.

However, there is another way. Although this also demands resources, the full exploitation of which lie in the future, these seem quite reasonable, straightforward even, when you compare them against what Alcubierre and others of a similar ilk propose. This way is to use Quantum Mechanics.

It's now over a century since Max Planck started a revolution by suggesting that light was emitted in tiny packages—as photons. He lit a torch (if you'll forgive the pun) that was eagerly carried onward by Einstein, Bohr, de Broglie, Schrödinger, Heisenberg, and a host of other brilliant people. To this day we are still grappling with the resulting practical and philosophical consequences. We've all heard of the examples: cats that are neither alive nor dead, objects that can magically pass through solid walls, and particles that can instantly affect each other at opposite ends of the Universe. Strange counterintuitive results, from a theory beyond our normal human experience.

In the everyday physics that we all learnt at school (called Classical or Newtonian Mechanics), we generally know exact values for an object's parameters in time and space. For example, we can write down equations for its precise position, velocity, momentum, and energy. In the quantum realm, however, we don't usually have exact values for these parameters—there is uncertainty. This uncertainty can actually extend to an object's position in the whole of space. You might be familiar with a well-known, early formulation of this idea known as the Heisenberg Uncertainty Principle.

This uncertainty is encapsulated at the heart of quantum mechanics by a construct called the "wave function." The wave function is a mathematical expression that varies in both time and space. It contains everything known about the real object it is describing. For example, it can be interrogated (using special mathematical functions called operators) to yield up equations for parameters like momentum and energy. These equations express the uncertainty just mentioned, and only when an attribute is carefully measured through its interaction with another entity will the wave function "collapse" to a definite point and yield a precisely defined value.

You can think of the wave function as being like a mist. It commonly appears, for example, as a localised cloud, concentrated in the middle and progressively more rarefied toward its edges—rather like an isolated fluffy fair-weather cloud on a summer's day. The mist represents where the object actually is—and the probability of finding it in a particular position in the cloud is its density value squared at that point. In other words, the thicker the mist, the more likely the object is to be found there.

The uncertainty of a real physical object's position as expressed by its wave function is not a trick or error caused by our inability to measure it correctly. It is a real and fundamental part of nature. Between interactions or measurements, the object's very essence is somehow "smeared" within the wave function. To this day we don't know what its reality is, when it is in this state—or if it can even be described as having any reality at all!

The wave function itself can expand, contract, and change its shape through the influence of the surrounding environment. It can spread through the entire Universe or be very confined to a particular volume of space (in which case it's often referred to as a wave packet).

We know *nothing* about what's happening inside the mist of the wave function. Thus, quantum mechanics is all about probabilities—in other words, it is controlled by statistics and not by determinism like classical mechanics. The two descriptions of an object's behavior, the classical and the quantum, are not compatible—they are speaking different mathematical and physical languages.

Let's pause to think about what this means for just a second. What we are actually saying is that the wave function is where classical physics completely breaks down—basically its limit. The dynamics inside the wave function are totally different to those outside. One startling implication of this is that quantum and classical mechanics (including relativity) can never be united by themselves. They are incompatible—as though the quantum realm is a crack in the very fabric of classical space and time, through which we glimpse a different reality—a crack that perhaps originated at the very formation of the Universe. Only if a deeper underlying structure is discovered will these two aspects of reality, classical and quantum, be reconciled. Since this deeper reality, if it exists, might well be outside the fabric of our Universe, it's possible that we may never uncover it.

As a slight aside, those familiar with some of the more modern speculations of theoretical physics might note the similarity of this idea to the so-called "holographic universe" conjecture. This supposes that our quantum pixilated existence is rather akin to a holograph projected into the Universe from a boundary that you might think of as its edge.

Now, here's the rub—and the very basis of the quantum mechanical star-drive: If the quantum wave function exists outside the classical Universe, then the rules of classical mechanics no longer apply within it—including the speed of light velocity limit. Dynamics in this "quantum crack" are not restricted by relativity. In other words, the idea of the quantum drive is to manipulate the wave function of the object so that it appears in the area where we wish to transport the object—so allowing it to appear there, when its wave function collapses. Let's delve deeper into the more subtle points around this.

Now, if you think about this a little, you'll see that what's important here for faster-than-light travel is not just what happens inside the wave function, but the propagation of the wave function itself. Can it extend or travel faster than light?

The great German physicist Max Born thought not, stating: *"The motion of particles follows the laws of probability, but the probability itself propagates according to causality."* For reasons we need not go into here, objects that travel faster than light violate causality. However, closer examination shows Born's statement to be untrue—to quote a recent best-selling book on quantum mechanics[1] by the popular science presenter and physics professor Brian Cox, the wave function can instantaneously exist anywhere throughout space: "*The particle can be anywhere else . . . at every conceivable point in space.*"

Mathematically, the evolution of the wave function is governed by the famous Schrödinger Equation. This equation tells us, given a known set of circumstances, what the wave function will do next. For those with a little mathematical knowledge I'll briefly explain this—but if the equation puts you off, just skip the next paragraph—it won't lessen the argument. The Schrödinger equation is shown below (Ψ is the symbol for the wave function):

$$i\hbar\frac{\partial}{\partial t}\Psi = \hat{H}\Psi$$

Don't worry about the $i\hbar$ at the start of the formula—just think of this as a constant. The $d\Psi/dt$ term is how fast the wave function is changing (its derivative or rate-of-change)—and is what we'd like to know here. The $\hat{H}$ with the little hat extracts the total energy of the system from the wave function and environment (it is one of the "operators" which I mentioned earlier—and is called the "Hamiltonian").

So the formula says that how fast the wave function changes in time depends on the energy of the system. Notice that there's nothing about the speed of light in the equation—it just says that the higher the energy, the faster the wave function can evolve. In other words, given the right circumstances, the wave function can spread through the entire Universe—and the object can potentially appear anywhere (which is what Cox stated in his book, quoted earlier).

In fact, right back to the very origins of quantum mechanics, many scientists had noticed that the theory allows faster than light travel and published peer-reviewed papers saying as much. It was seen in practical experiments at Bell labs by L A MacCall as far back as the 1930s, who noted,[2] "*When a particle tunnels through a barrier, it does so without appreciable delay,*" and even Eugene Wigner, a Nobel prize-winner, reached the same conclusions in the 1950s[3]; other examples[4] can be found in more recent publications too.

Two well-known results of quantum mechanics demonstrate this faster-than-light ability very well. The first is "tunnelling" (mentioned briefly in the paragraph above)—a uniquely quantum phenomenon in which objects can suddenly disappear from one side of a solid barrier, only to reappear instantaneously on the other side. It is truly one of the most surprising, counterintuitive, and apparently magical results of quantum theory. However, it arises rather plainly from the mathematics of the Schrödinger equation and is relatively easy to observe in experiments. In fact, all that really happens is that the wave function collapses on one side of the barrier (and the particle becomes visible), it then reestablishes itself, and the probabilistic nature of the system immediately manifests the particle on the other side when the wave function collapses there.

The second scenario is the confinement of an object in a so-called "potential well." Basically, this is just a "cage" that traps the particle; this cage typically consists of a strong confining force—usually gravitational or electromagnetic. In such a situation, the wave function is suddenly present throughout the well, and so the object can appear instantaneously anywhere within it when its wave function collapses. In fact, in this situation, Schrödinger's equation mathematically reduces to a special form that doesn't include time at all. This version of the equation is called the "time independent" form and indicates that a nonzero probability of finding the object exists throughout the enclosed space instantly.

So, why don't we normally see these bizarre effects in nature? Well, the waveform collapses, and the object finally gives away its position whenever it interacts with something else. This "something else" could be another particle of matter or a photon of radiation. Normally objects are bathed in such radiation and subjected to a constant bombardment of particles—for example by air molecules, natural radioactivity, or even cosmic rays. They also generate their own cloud of virtual particles and different parts of the wave function can interfere with each other—localizing the effect to something that resembles a single point (which you might remember is usually called a wave packet, rather than a wave function). There is also a suspicion among some researchers (although not widely accepted) that perhaps these virtual particles and the other interference cause an almost drag-like viscous effect on the object—and this might actually be the underlying cause of the light-speed limitation of normal free objects. This would make the light-speed limitation part of another newer quantum theory called Quantum Electrodynamics or QED. If this turned out to be true, the effect might be detectable as a slight variation of the speed of light limit in free matter particles that were partially shielded. For all these reasons, the nonlocalized nature of the wave function is seldom on display.

However, this is not to say that we can't ever see it—or make it manifest. We just need to provide the right circumstances. Although we tend to think of quantum mechanics as only appearing at the scale of atomic or subatomic particles, modern experiments have shown its effects at much larger scales. Examples of this include the various macroscopic mechanical resonators and cantilevers that have been carefully designed to exhibit quantum behavior.[5] Another system displaying such behavior is the Bose-Einstein condensate, in which a large group of particles can again be forced to act in a quantum manner, even at large scales.

In fact, the exact quantum relationship between single particles and objects made from assemblies of particles is not entirely clear yet—and to exhibit the behaviors we are discussing, it might prove necessary to use substances like the Bose-Einstein condensate because of their ability to coalesce into a single quantum state. Several other systems and materials behave similarly, including some very cold fluids (called "superfluids"), but only under certain specific circumstances. It may also be eventually possible to shield multiparticle systems using substances like the condensate.

The other secret of seeing quantum behavior is to isolate the system in question from outside interactions. As we discussed earlier, it is these interactions with the outside world that cause wave functions to collapse. The state before this happens (when the wave function is intact) is sometimes called a state of "superposition" because all possible "ways of being" (states) of the system are superimposed on each other—when the wave function collapse occurs, the superposition simply reduces into a single defined state.

The outside interaction, as we learned above, can be due to collision with radiation or matter. So, if we can shield or isolate our system from these, then we can establish the quantum wave function and therefore push the object outside the rules of classical physics—and the light-speed restriction.

This shielding might be done in a variety of different ways: by cooling the surroundings to reduce radiation and thermal excitation; by materially protecting the object from incoming influences; or by using physical fields to deflect incoming particles and photons away—or some combination of all of these. Of course, most of this is easier to do in the depths of space with its ultra-hard vacuum, rather than on crowded Earth.

If you think about these requirements, it begins to make sense why, at present, we've only managed to make very small objects show these effects—providing this level of protection becomes progressively more difficult as size increases. However, as we advance, new ways to let objects manifest their quantum nature will be discovered, and the existing ways improved and developed. This is certainly much less of an "ask" than providing the sorts of exotic energies that relativistic space-time manipulation of creations like the Alcubierre drive demand.

So, in the future, what resources might a quantum drive require, and how might it work? Let's start by asking what it may need to function. Well, certainly some versions will need a created potential-well to guide and shape the wave function. The trouble with this is that the well needs to be *in situ* before travel can take place—because its influence is due to a force of nature (like gravitation or electromagnetism) that only travels at the speed of light. If you think about it, though, establishing these "guides" beforehand is not quite such a big deal—after all, you don't build a new tunnel each time you need to travel through one on a train! It might also be possible to use naturally occurring wells, too.

Then there's the shielding. Again, this might require large energies in order to be effective with bigger objects—for example, to generate protected bubbles or corridors in space. So, these aspects of the system might directly require the power of the stars themselves to generate, and new metamaterials and radiation shaping structures to control at large scales. Far-future stuff—but not impossible as we advance.

You might start to see that some of these transport ideas lend themselves not to traditional ships as such, but more to systems akin to science fiction's Stargate. A portal into which an object is placed, its essence shielded from the outside world, and its surroundings shaped by intense fields generated and manipulated by the machine.

Of course, even with all this manipulation of the wave function, you only have so much control—the object can manifest anywhere within the bounds defined by the function—it's all guided by probabilities, remember! So rather like the "Infinite Improbability Drive" (a good name for a quantum drive, don't you think?) in the *Hitchhiker's Guide to the Galaxy,* outcomes are driven, within the bounds of the wave function, by chance. We just shorten the odds by adjusting the potential well to shape the possible results to a range of acceptable probabilities that are in-line with our needs.

There are other options, however. The more one ponders the possibilities, the more interesting potential modes of operation there are. For example, rather than make single giant leaps across space, one can imagine ways in which the system might be configured to make many much shorter (minute even) hops, which could then be strung together to form a larger journey.

Or the basic principle could be combined with other interstellar travel possibilities. Take for example a wormhole—also known as an "Einstein-Rosen Bridge." These are space-time constructs, similar in some ways to black holes, in which the fabric of space is bent round to form a sort of tunnel between two distant regions. The idea is that objects could transverse this tunnel and thereby circumvent travelling the "long way round" through normal, relatively flat space-time.

Wormholes have not yet been shown to exist, and if they do, passing an object through them in the normal sense is very problematic because of their physical dimensions and the extreme curvature of space around them. If they do exist, they may also not be stable and therefore prone to collapse and disappearance after a very short time.

However, suppose that we combined the idea of a wormhole with the quantum wave function. If a suitably shaped wave function is present, sufficiently near the mouth of the wormhole, then, just as with a solid barrier, part of the function would appear on the exit side of the hole—and the object could tunnel though. During the tunnelling process, our object doesn't penetrate the bridge in any physical sense and therefore is unaffected by the space-time warping—and since tunnelling is essentially instantaneous, the potential transient nature of the hole is not a deal-breaker either.

Given the constraints of making any object show it's wave function at the large scale, it's a matter of debate whether we'll ever succeed in the quantum transportation of complex or even organic matter. We might, at the beginning anyway, have to be satisfied with lesser fare—simple objects or machines, cleverly manufactured from substances that can be manipulated at the particle level to yield the quantum states of matter most amenable to our ends.

Now through all this, you may have been asking yourself an important question. In an earlier paragraph I mentioned that faster-than-light travel violates causality. So is this not the case here? Will the Universe not just protect itself against the heresy of quantum starships? Well, not necessarily. What is prohibited by relativity is *travel* through space faster than light. However, the system I've just explained doesn't do this—it doesn't travel—it simply blinks out of existence in one position and reappears instantaneously at another. You might remember that this is also what the tunnelling particle did when traversing its barrier. This avoids many of the mind-bending problems with causality that worry physicists.

And so there we have it. I would propose that quantum mechanics is a much better bet as a path to the stars than the exotic relativity drives that are usually poposed. To exploit the quantum path, we would probably have to expend huge quantities of energy in order to form powerful force fields and potential wells. We'd then have to use exotic (but known to exist) states of matter that could form the right type of quantum states. Finally, we'd have to devise ways of shielding all this from outside influence.

This might seem like a very tall order indeed, but it's as nothing to the "ask" of Alcubierre and similar space-warping drives: it doesn't need matter or energy types that have never been shown to exist nor powers greater than the Universe can provide. Yes, it may seem like science fiction now, and some will argue that it can't or won't exist. But given the rate of human advancement and our endless ingenuity—if we survive long enough—anything that can be made eventually will be. Quantum mechanics is the only area of the sciences, that we know about, that really does lie outside the constraints of classical physics—which is what we need for faster-than-light travel—and so the quantum star-drive is the long-odds horse I'd put my money on.

Endnotes:

[1] B. Cox and J. Forshaw, *The Quantum Universe,* Penguin, 2011, p. 46.

[2] L. A. MacCall, Physical Review 40, 1932, p. 621. Also see New Scientist no 1971.

[3] E. P. Wigner, Physical Review 98, 1955, p. 145.

[4] C. MacLeod, Quantum Mechanics and travel to the stars, Nexus, 21 (5), 2014. pp. 43-48. Available on-line: https://pureadmin.uhi.ac.uk/ws/portalfiles/portal/1903123/Nexus_article_v3.pdf

[5] A. D. O'Connell et al, Quantum ground state and single-phonon control of a mechanical resonator, Nature (464), 2010, pp. 697-703. Also see New Scientist no 2768.

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