PARTICLES VERSUS WAVES: EXORCIZING A PHYSICS DEVIL AND PEERING INTO THE HUMAN MIND

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Summary: Can something be both a particle and a wave? Most people would say not, but it has been known since the early 1900s that in certain experiments an electron (say) can show both kinds of behaviour. We recently found a way to resolve this apparent paradox that is creating a bit of a buzz.

Question (deep): How can something be both a wave and a particle?

Answer (shallow): When it's a "wavicle."

If you fire a bullet, it moves according to the laws of physics, and by means of slow-motion photography you can find exactly where it is in space at any time. The bullet is a particle, with all the properties of localization with which we are familiar. If

the bullet hits a cardboard target, you expect it to pass through, with a well-defined path on the other side. You do {not} expect that the bullet will mysteriously lose its identity, transforming itself into a spread-out disturbance, and even showing the interference patterns typical of a wave. Yet this is what appears to happen if we carry out a similar experiment on the microscopic scale, using (say) an electron and a screen with slits in it. Hence, that baffling situation whose apparent illogicality has caused many a physics student to curse. In the average textbook, the basic set-up is called the double-slit experiment, and the general phenomenon is called wave-particle duality. But giving things names does not necessarily lead to an understanding of their physics, and many physicists regard the invention of the tag "wavicle" as a cop-out.

Physicists, as a result of their belief in the underlying logicality of the world and their training, do not like paradoxes. And the deep thinking necessary to resolve apparent paradoxes has frequently led to great advances in our understanding.

A prime example of this is Olbers' paradox. In its modern form, this posits a universe that is eternal, unbounded in ordinary space, and populated by a uniform distribution of slowly-moving but bright galaxies. Then the number of sources visible to an observer goes up as the cube of the distance, whereas the intensity of any one only goes down as the inverse square of the distance. This implies that the night sky should be ablaze with light, not dark as anybody can see. Olbers' paradox dates from at least 1826, but was only laid definitively to rest in 1987. (See Astrophysical Journal vol. 317, p. 601, or the non-technical version which appeared two years later in Sky and Telescope. vol. 77, p. 594.) The resolution depends critically on the existence of the big bang, which by limiting the history of the universe also limits the time over which galaxies have been shining, leading to a dark night sky.

There is an important message here: a local observation such as the few photons per second entering the eye of a person out for a night stroll, can depend on a global factor such as the existence eons ago of the big bang. There is, in the case of Olbers' paradox, a kind of chain effect involving the laws of physics, whereby the small things that we observe here and now depend on the large things that happened there and then. Could it be, in the case of the double-slit experiment and wave-particle duality, that a similar kind of resolution is possible? That is, can we obtain an explanation of how something can act like a particle and a wave on the small scale, by appealing to the laws of physics as they are understood on the large scale?

The answer appears to be: Yes. This, however, is subject to the proviso that we are willing to look beyond the (simple) rules of local physics, and consider the (more complicated) laws of global physics. The latter involve Einstein's general theory of relativity, which is rich in concepts which while normally applied to astrophysics can equally well be used in the domain of atomic physics. Both subjects involve laws of

mechanics, but while these match numerically, they have different origins conceptually. For example, quantum theory in its simplest version of wave mechanics is based on concrete and unchangeable labels for space and time, whereas general relativity even in its local form incorporates the ability to change and mix the labels of spacetime. This is clearly relevant to our wish to resolve wave-particle duality, because we need to find two different but equivalent descriptions of the same thing. The way in which this can be achieved was outlined in a recent paper (Journal of General Relativity and Gravitation, May 2006). We did not wish to fuel the traditional feud between physicists who deal with small (quantum) and large (classical) systems, so we titled our article “Wave Mechanics and General Relativity: A Rapprochement”.

The bridge between our views of small and large physics turns out to depend on the concept of “isometry”. This is a word which, in straight translation, means “equal measure”. There are lots of examples of isometries in everyday life, but they are frequently obscured by our preconceptions. A particularly ingenious one opens the movie “Cosmic Zoom”, which is used to teach students about the scales of objects in the world, from quarks to quasars. We see what is apparently a jumbo-jet landing at a large airport. It taxies ponderously towards buildings seen vaguely in the distance, and we can almost feel the anticipation of the passengers as they prepare to disembark … Then a giant human hand reaches down, picks up the airplane, and the camera zooms back to reveal Legoland! We have been watching a model, not the real thing.

Isometries can be illustrated by models (as long as they are ones made to scale), but their essence is mathematical. A more technical – but still very simple – example involves the distance between two nearby points in ordinary (3D) space. If we use Cartesian coordinates, this is given by the familiar formula of Pythagoras, $ds^2 = dx^2 + dy^2 + dz^2$. But if we use spherical polar coordinates, it is given by $ds^2 = dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2)$. These expressions are equivalent. In the first, we measure the square of the distance in terms of 3 lengths (x, y, z). In the second, we measure it by 1 length and 2 angles $(r, \theta, \phi$ for the radius and measures akin to latitude and longitude). The choice of which set of coordinates to use is ours, and depends on convenience. We would naturally use the first to describe something like a picture on a flat sheet of paper, and the second to describe something like the continents on the spherical surface of the Earth.

For the universe according to Einstein, we need to add the time *t* to the above, to form 4D spacetime. However, this needs to be curved and not simply flat as before, if we are to describe the force of gravity. The resulting theory, general relativity, is very successful in modelling the properties of large, massive objects, such as the Sun. The theory is based in part on the Principle of Covariance, which is basically a restatement of

our ability to choose the coordinates (whereby we describe objects) as we please. Within this scheme, isometries are particularly important, because they provide different descriptions of the <u>same</u> object. This said, it should be added that some isometries are exceedingly complicated mathematically, and require great skill to work into other more familiar forms where we recognize what they mean physically.

At this point, the reader may ask why relativists bother to study isometries. The answer is that if we find a solution of Einstein's theory where the equations have one form, we can often gain more insight into what that solution means if we cast the equations into another form. For this reason, isometries have been studied extensively by such doyens of the subject as the late Nathan Rosen (in regard to black holes) and Wolfgang Rindler (in regard to the big bang). However, there are further uses for isometries, especially in regard to elementary particles. Attempts to model these using straight general relativity have often been made (e.g., by G. 't Hooft who tried to model particles as spinning black holes). These did not meet with much success, mainly because the 4D spacetime of Einstein gravity is not "big" enough to incorporate the other 3 known forces which affect particles. (These are called, somewhat boringly, the strong and weak interactions, the other one being electromagnetism.) It is now popular to look for ways to unify the 4 known forces using "spaces" of higher dimensions. There are several such theories, each motivated by different approaches to the symmetry groups of the particles, which are classifications of their physical properties such as charge and spin. Hence 10D supersymmetry, 11D supergravity and 26D string theory. Looking for isometries in spaces of such high dimensions is both necessary and daunting. Luckily, it is generally acknowledged that the low-energy limit of these theories involves 5D, which is also the simplest extension of general relativity. Indeed, results on the isometries of 5D spaces for both particles and cosmology have been known for decades. (See for the electron P.A.M. Dirac, Annals of Mathematics, vol. 36, p. 657, 1935; and for the big bang H.P. Robertson in his book with T.W. Noonan, Relativity and Cosmology, Saunders, Philadelphia, p. 413, 1968.) Thus for a particle like the electron and the wave behaviour it shows in an experiment like that of the double-slit, we have some results in 5D which help us towards an isometry that shows how one thing can have two guises.

Experiments have also to be taken into account, of course. In this respect, there is one rule which is obeyed by all known particles to high accuracy. Let E be the energy, p the momentum in ordinary (3D) space, and m the rest mass. Then experiments with various kinds of accelerators have shown that there is a simple relation between these quantities. It is actually connected with a theoretical concept called Lorentz invariance, which is a symmetry common to all particles that move in the flat spacetime of special relativity, which is the local limit of curved general relativity. (For a non-technical

review, see M. Pospelov and M. Romalis, Physics Today, vol. 57, no. 7, p. 40, 2004.) If c is the speed of light, the relation we need to respect is $E^2 = p^2c^2 + m^2c^4$.

With this formula as a guide, and with the other results we have sketched above to assist, we are in a position to pose our question: Is there an isometry between a particle and a wave which shows that they are the same thing viewed in different ways?

To answer this, imagine you are aboard a boat on a stormy sea. If the boat moves along freely, close to the speed of the waves, you will hardly notice the latter. If on the other hand the boat is anchored to the seabed, you will see the waves rushing past you. This means that whether you have a smooth existence or a bumpy one depends to a degree on your own state, which in relativity is defined by the coordinates. By changing these judiciously, we can go from the straight-line motion of a particle to the up-and-down motion of a wave. To do this consistently, it is helpful to use a kind of ladder, starting at 2 dimensions and going up to 5 dimensions. The middle part of this, corresponding to spacetime, then yields wave-like analogs of the energy and the momentum (which has 3 independent components). Let us label these $\tilde{E}$ and $\tilde{p}$,where the squiggles mean that we have the wave versions of the quantities E and p for the particle noted above. So far, there is nothing very challenging about our approach, and most relativists would accept it as a consequence of Einstein's Principle of Covariance (see before). However, we now run into a conceptual problem to do with the third ingredient of mechanics, the mass *m*. This is not usually treated as a coordinate (like *xyz*), so how can we transform it to a wave? To do this, we used a nifty mathematical trick, which at the time we thought was original. We took a known 4D isometry (in books like that of Rindler it is known as the Milne/Minkowski transformation), extended it to 5D, and then came back to 4D. This may sound like going around the house to get to the door, but if you have no other way to access the door (mass) then you have to do it. In fact, physicists do it regularly in more simple problems, where they add an extra axis, go around something with a special value (the "pole"), and thereby evaluate it. The result for our case is a quantity $\overset{:}{m}$ which is the wave version of the mass. To finish the analysis, we put all of the components together, and found $\overset{:}{E}^2 = \overset{:}{p}^2 c^2 + \overset{:}{m}^2 c^4$.

This relation for a wave agrees exactly with the one above for a particle, and proves the case that the two things are in a geometrical sense equivalent. But now, a note of pathos in the midst of this proud physics. When we did the above calculation in 2005, we were unaware of Dirac's paper on the subject in 1935. True, only one person among the many who responded to our work knew of Dirac's article; and true it was published in a place that is now seldom visited; and true it used the cumbersome language of operators rather than the sleek symbolism of isometries. But Dirac's results parallel our own. Historians of science, given the 70-year lapse between the works, may be tempted to

make disparaging remarks about the obscurity which attends the so-called knowledge explosion. However, we prefer to be more positive: If a difficult problem is analysed by different people using different approaches and the result is the same, then you can have confidence that you have the right answer.

The result we have described goes beyond a resolution of wave-particle duality. For example, our approach shows that mass can be considered as a wave. Dirac's approach led him to discuss the "real" and "imaginary" parts of the mass of the electron, which is mathematical language for the two orthogonal directions along which we measure the properties of a wave. In hindsight, this may not be so surprising. Of the 3 usual quantities of mechanics, L. de Broglie showed how to treat the energy and momentum as waves. So why not treat the third element – mass – as a wave?

This is possible, as we have seen; but it is somewhat disquieting. Consider a billiard ball. A pool player normally regards the mass as a quantity localized in the ball. He does not think of it as a wave spread between the cushions of a snooker table. However, he might make the mental switch, if he regarded the cue also as a tube of waves which resonates with and locks onto the wave-like ball, producing a perfect shot into the corner pocket.

Quantum mechanics has a philosophy which loves to play with the interchangeability of particles and waves. However, it is bedevilled with problems of interpretation. In the view of the metaphysical Copenhagen school, each particle has associated with it a wave, which collapses to a point when we choose to make an observation. This sounds miraculously unlikely to many physicists. Better, is to admit that particles and waves are equally valid constructs, and that the choice of description lies with us.

This view puts the onus on us to understand the world; and not on it to go through contortions so we can feel comfortable about it. Our view agrees with that of the eminent British astrophysicist Sir Arthur Eddington (1882-1944). His writings include a much-quoted analogy, involving a fisherman. The fisherman's net has a certain mesh size, so he infers (wrongly) that all fish in the sea must be bigger than this. Reading Eddington's works, it is apparent that many aspects of physics involve subjective elements, which follow from the way in which we interpret the external world. Our need to understand things as particles or waves is an example of this.

Eddington's opinions, as developed by Sir F. Hoyle, have recently been made more concrete by Sir R. Penrose. He has argued that the human brain can amplify microscopic quantum influences so that they have macroscopic effects. This idea, while speculative, explains many facets of how we interact with the world. However, even if it turns out to be correct, it will probably represent but one aspect of the brain's capabilities.

The human mind, as supported biologically by the brain, is a remarkably devious device. If it can handle the equivalence of a particle and a wave, what else can it do?