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Wave-Particle Duality

Of all the mysteries, puzzles, and paradoxes associated with modern physics, none is more profoundly metaphysical than the strange connection between waves and particles in quantum mechanics. And no philosophical method is better positioned to provide a metaphysical explanation than information philosophy, with an information analysis of the physics and the fundamental nature of physical reality, the so-called “quantum reality.”

Most surprisingly, the solution to this most modern of scientific problems throws new light on perhaps the oldest philosophical problem, the ancient question about the existential status of ideas, and the relation between the ideal and the material.

Put most simply, the quantum wave function is an idea, pure information about the possible places that matter may be found. And perhaps most shocking, we can show that this abstract idea has causal power over the paths of the concrete particles, even as we can only learn about their paths statistically and not individually.

We present our solution with a historical view of the problem through the eyes of ALBERT EINSTEIN, who worried for decades about fundamental conflicts between quantum theory and his theories of special and general relativity. Using his thinking, we shall resolve the conflict with special relativity and show that in quantum mechanics the distribution of matter in space plays a role somewhat analogous to its role in general relativity, specifically, space having an influence on the motion of particles of matter.

No one understood wave-particle duality better than Einstein. Nevertheless, no one was more misunderstood than Einstein, by both his opponents and by his most avid supporters. No one thought about the problem longer. For over three decades from 1905 until 1935, Einstein had critical new insights into waves and particles that are today central parts of quantum mechanics. By comparison, the work of Einstein’s opponents, the supposed “founders of quantum mechanics,” was done in less than three years, from 1925 to 1927, and their theories have left scientists



and philosophers with a tangled mess and dozens of conflicting “interpretations of quantum mechanics,” all of them attempts to replace the original and muddled “Copenhagen interpretation.”

The Heart of the Puzzle

Can something be, at one and the same time, both a discrete discontinuous particle (WERNER HEISENBERG) and a continuous wave field (ERWIN SCHRÖDINGER)?

The answer is similar to the solution we proposed for several ancient metaphysical paradoxes - something can be both a concrete substance and an *immaterial* form, both material and ideal.

In chapter 17 we contrasted necessity and contingency. We associated necessity with determinism and the logically *a priori*, contingency with chance and the *a posteriori*.

We can now say that the wave aspect of a quantum is perfectly deterministic and the particle aspect is fundamentally random.

For the quantum physicist doing calculations, it is always *either* a wave or a particle. The time evolution of a quantum system, an electron or a photon, for example, proceeds in two stages, similar in many ways to our two-stage model of free will. (Particles do not have a will, but, like humans, they are free, not pre-determined.)

The first wave stage is when the wave function explores all the *possibilities* available, given the configuration of surrounding particles, especially those nearby, which represent the boundary conditions used to solve the Schrödinger equation of motion for the wave function. Because the space where the possibilities are non-zero is large, we say that the wave function (or “possibilities function”) is *nonlocal*. The time evolution of the possibilities function is completely deterministic.

The second stage is when a particle is found somewhere. An observer can not gain any empirical knowledge unless new information is irreversibly recorded, e.g., a particle has been localized in the experimental apparatus. This second stage is when the particle interacts with the apparatus’ particles, leaving a record of its interaction. One of the nonlocal *possibilities* has then been “*actualized*.” The particle is now localized, but the new position is completely random, anywhere the possibilities function is non-zero..



Note that when particles are observed, they are totally localized. They are never found partly here, partly there.

When you hear or read that electrons are *both* waves and particles, you can operationally think “either-or” - first information in a wave of *possible* locations, then an *actual* particle location.

Think of the paradox or perhaps the irony in this temporal sequence. First, the possible positions evolve through space *deterministically*. The *average* position actually follows a classical path, just as the average behavior of large numbers of quantum particles approaches classical behavior. We call this “adequate determinism.”

But then the actual position where an individual particle is found is *indeterministic*. The time that a radioactive particle decays is completely random. The time and direction a photon is emitted by an atom is the result of ontological chance, as Einstein first saw in 1916.

Many critics of quantum theory complain that these two aspects are logically contradictory. They may be antithetical, but they are not contradictory. Probabilities are determined, but the possibilities that are actualized are the result of ontological chance.

Let's now ask what it is that determines the evolution of the wave or “possibilities” function. Since we argue that the wave function is pure information, we must ask where does that information come from? What information in the physical world leads to the information about possible physical locations for particles?

The answer is quite simple. It depends only on the wavelength of the particle and the boundary conditions of the experiment. In the case of the two-slit experiment, boundary conditions are the wall with two slits and the detection screen.

But this has profound implications. Questions like which slit did the particle go through? or how does the particle going through slit A know that slit B is open?, can now be answered clearly.

The interference conditions that produce maxima and minima (even null points) in the number of particles found are present in the space where the particles will be allowed to travel.

Thinking temporally, the probability amplitudes and the possibilities function are present in the space before any particle arrives, determined by the particle wavelength and the spatial geometry.



We can note a loose parallel with Einstein's general relativity, which reimagines dynamical forces as the spatial curvature caused by the overall matter distribution. Particles are determined to follow shortest-distance paths (geodesics) that are present in space.

In our information analysis of quantum mechanics, particles follow paths determined by the probabilities function present in space, which is determined by material boundary conditions.

In both relativity and quantum mechanics, information present in space has a *causal* influence on the motion of material objects.

This is far from a reconciliation of quantum mechanics with general relativity. That requires giving up Einstein's field picture, with physical objects described by classical variables that depend only on local coordinates in his four-dimensional space-time continuum. Reconciliation means a replacement of continuous fields with a particles picture that has nonlocal and statistical behaviors.

Einstein knew that his dream of a unified field theory may not be possible. In 1949 he asked about the theoretical foundation of physics, "Will it be a field theory [or] will it be a statistical theory?"

But our information picture does reconcile quantum mechanics with special relativity, which was Einstein's earliest concern about nonlocality. The mistaken idea that the wave *is* in any sense the particle leads to the false belief that something (matter or energy, or at least a signal) must move when the wave function "collapses."

In our information analysis, all the information needed for quantum interference effects is already present in the space itself, e.g., the "knowledge" that slit B is open. With slit B closed, particles are distributed one way. With both slits open, positions on the screen that had particles with only A open, now have no particles.

The pure information about boundary conditions for waves in space is influencing the motion of material particles. But no part of the probability wave amplitude or the possibilities function has to move to the point where a particle is found, as was shown in Figure 20-2 of chapter 20. The interference pattern depends only on the particle wavelength and the boundary conditions, not on the moving particle. We can think of it as a standing wave.



The History of Waves and Particles

That a light wave might actually be composed of quanta (later called *photons*) was first proposed by Einstein as his “light-quantum hypothesis.” He wrote in 1905:

In accordance with the assumption to be considered here, the energy of a light ray spreading out from a point source is not continuously distributed over an increasing space but consists of a finite number of energy quanta which are localized at points in space, which move without dividing, and which can only be produced and absorbed as whole units.¹

On the modern quantum view, what spreads out to fill space is a “nonlocal” wave of probability amplitude, which gives the possibilities for absorption, followed by a whole photon actually being absorbed (“localized”) somewhere.

In 1909, Einstein speculated about the connection between wave and particle views:

When light was shown to exhibit interference and diffraction, it seemed almost certain that light should be considered a wave...A large body of facts shows undeniably that light has certain fundamental properties that are better explained by Newton’s emission theory of light than by the oscillation theory. For this reason, I believe that the next phase in the development of theoretical physics will bring us a theory of light that can be considered a fusion of the oscillation and emission theories...

Even without delving deeply into theory, one notices that our theory of light cannot explain certain fundamental properties of phenomena associated with light. Why does the color of light, and not its intensity, determine whether a certain photochemical reaction occurs? Why is light of short wavelength generally more effective chemically than light of longer wavelength? Why is the speed of photoelectrically produced cathode rays independent of the light’s intensity? Why are higher temperatures (and, thus, higher molecular energies) required to add a short-wavelength component to the radiation emitted by an object?

The fundamental property of the oscillation theory that engenders these difficulties seems to me the following. In the kinetic

¹ Einstein (1905) “A Heuristic Viewpoint on the Production and Transformation of Light,” *Annalen der Physik*, vol.17, p.133, English translation - *American Journal of Physics*, 33, 5, p.368



theory of molecules, for every process in which only a few elementary particles participate (e.g., molecular collisions), the inverse process also exists. But that is not the case for the elementary processes of radiation.

According to our prevailing theory, an oscillating ion generates a spherical wave that propagates outwards. The inverse process does not exist as an elementary process. A converging spherical wave is mathematically possible, to be sure; but to approach its realization requires a vast number of emitting entities. The elementary process of emission is not invertible. In this, I believe, our oscillation theory does not hit the mark. Newton's emission theory of light seems to contain more truth with respect to this point than the oscillation theory since, first of all, the energy given to a light particle is not scattered over infinite space, but remains available for an elementary process of absorption.²

Here Einstein sees the emission and absorption of radiation as *irreversible*. This microscopic irreversibility explains the macroscopic irreversibility of statistical mechanics and thermodynamics.³

Dueling Wave and Particle Theories

Not only do we have the problem of understanding wave-particle duality in a quantum system, we have a full-blown wave mechanics theory (de Broglie and Schrödinger) versus a particle mechanics theory (Heisenberg, Max Born, Pascual Jordan).

Before either of these theories was developed in the mid-1920's, Einstein in 1909 showed how both wave-like and particle-like behaviors are seen in light quanta, and in 1916 that the emission of light is done at random times and in random directions. This was the introduction of ontological chance (*Zufall*) into physics, over a decade before Heisenberg announced in his "uncertainty principle" paper of 1927 that quantum mechanics is *acausal*.

As late as 1917, Einstein felt very much alone in believing the reality (his emphasis) of light quanta:

"I do not doubt anymore the *reality* of radiation quanta, although I still stand quite alone in this conviction."⁴

2 Einstein (1909) 'On the Development of Our Views Concerning the Nature and Constitution of Radiation,' *Phys. Zeit* 10: 817.

3 See chapter 25 of *Great Problems of Philosophy and Physics*.

4 Einstein (1917a) quoted by Abraham Pais, "Subtle is the Lord...", p.411



Einstein in 1916 had just derived his A and B coefficients describing the absorption, spontaneous emission, and (his newly predicted) stimulated emission of radiation. In two papers, “Emission and Absorption of Radiation in Quantum Theory,” and “On the Quantum Theory of Radiation,” he derived the Planck law (for Planck it was mostly a guess at the formula to fit observations), he derived Planck’s postulate $E = h\nu$, and he derived Bohr’s second postulate

$$E_m - E_n = h\nu.$$

Einstein did this by exploiting the obvious relationship between the Maxwell-Boltzmann distribution of gas particle velocities and the distribution of radiation in Planck’s law. He wrote in 1917:

The formal similarity between the chromatic distribution curve for thermal radiation and the Maxwell velocity-distribution law is too striking to have remained hidden for long. In fact, it was this similarity which led W. Wien, some time ago, to an extension of the radiation formula in his important theoretical paper, in which he derived his displacement law...Not long ago I discovered a derivation of Planck’s formula which was closely related to Wien’s original argument and which was based on the fundamental assumption of quantum theory. This derivation displays the relationship between Maxwell’s curve and the chromatic distribution curve and deserves attention not only because of its simplicity, but especially because it seems to throw some light on the mechanism of emission and absorption of radiation by matter, a process which is still obscure to us.⁵

But the introduction of Maxwell-Boltzmann statistical mechanical thinking to electromagnetic theory has produced what Einstein called a “weakness in the theory.” It introduces the reality of an irreducibly objective and ontological chance!

Einstein saw that if light quanta are particles with energy $E = h\nu$ traveling at the velocity of light c , then they should have a momentum $p = E/c = h\nu/c$. When light is *absorbed* by a material particle, this momentum will clearly be transferred to the particle. But when light is *emitted* by an atom or molecule, a problem appears.

5 Einstein (1917) ‘On the Quantum Theory of Radiation,’ *Sources of Quantum Mechanics*, B. L. van der Waerden, Dover, 1967, p.63; *Physikalische Zeitschrift*, 18, pp.121–128, 1917



Conservation of momentum requires that the momentum of the emitted particle will cause an atom to recoil with momentum $h\nu/c$ in the opposite direction. However, the standard theory of spontaneous emission of radiation is that it produces a spherical wave going out in all directions. A spherically symmetric wave has no preferred direction. It can not cause a recoil.

In which direction does the atom recoil?, Einstein asked:

“Does the molecule receive an impulse when it absorbs or emits the energy ϵ ? For example, let us look at emission from the point of view of classical electrodynamics. When a body emits the radiation ϵ it suffers a recoil (momentum) ϵ/c if the entire amount of radiation energy is emitted in the same direction. If, however, the emission is a spatially symmetric process, e.g., a spherical wave, no recoil at all occurs. This alternative also plays a role in the quantum theory of radiation. When a molecule absorbs or emits the energy ϵ in the form of radiation during the transition between quantum theoretically possible states, then this elementary process can be viewed either as a completely or partially directed one in space, or also as a symmetrical (nondirected) one. It turns out that we arrive at a theory that is free of contradictions, only if we interpret those elementary processes as completely directed processes.”⁶

An outgoing light particle must impart momentum $h\nu/c$ to the atom or molecule, but the direction of the momentum can not be predicted! Neither can the theory predict the time when the light quantum will be emitted.

Such a random time was not unknown to physics. When ERNEST RUTHERFORD derived the law for radioactive decay of unstable atomic nuclei in 1902, he could only give the probability of decay times. Einstein saw the connection with radiation emission:

“It speaks in favor of the theory that the statistical law assumed for [spontaneous] emission is nothing but the Rutherford law of radioactive decay.”⁷

But the inability to predict both the time and the direction of light particle emissions, said Einstein in 1917, is “a weakness in the theory..., that it leaves time and direction of elementary processes to chance (*Zufall*).” It is only a weakness for Einstein, of course, because his God does not play dice.

6 Einstein (1917) ‘On the Quantum Theory of Radiation,’ p.65

7 Pais (1982) *Subtle is the Lord...* p.411



Einstein clearly saw in 1917 as none of his contemporaries did for many years, that since spontaneous emission is a statistical process, it cannot possibly be described with classical physics.

“The properties of elementary processes required...make it seem almost inevitable to formulate a truly quantized theory.”⁸

In his paper on the A and B coefficients (transition probabilities) for the emission and absorption of radiation, Einstein carried through his attempt to understand the Planck law. He confirmed that light behaves like waves (notably when a great number of particles are present and for low energies), at other times like the particles of a gas (for few particles and high energies).

Dirac on Wave-Particle Duality

“Quantum mechanics is able to effect a reconciliation of the wave and corpuscular properties of light. The essential point is the association of each of the translational states of a photon with one of the wave functions of ordinary wave optics. The nature of this association cannot be pictured on a basis of classical mechanics, but is something entirely new. It would be quite wrong to picture the photon and its associated wave as interacting in the way in which particles and waves can interact in classical mechanics. The association can be interpreted only statistically, the wave function giving us information about the probability of our finding the photon in any particular place when we make an observation of where it is.”⁹

Note that the information about the possibility of a photon at a given point does not have to be “knowledge” for some conscious observer. It is statistical information about the photon, even if it is never observed or recorded. Many years before the “founding” of quantum mechanics, Einstein realized that the connexion between light waves and photons has a statistical character. The wave function gives information about the probability of one photon being in a particular place. and not just the probable number of photons in that place. Einstein described this as “incomplete,” when compared to classical mechanics, which it of course is.

Schrödinger agreed that the light wave at some point is the probable number of photons there. MAX BORN’s “statistical interpretation” (the “Born Rule”) simply extended Einstein’s idea to electrons.

8 Pais, *ibid.*

9 Dirac (1930) *Principles of Quantum Mechanics*, 4th ed., Chapter 1, p.9

