The Rise and Fall of Wave-Particle Duality

Alan M. Kadin

Abstract:

A retrospective is presented of the rise and fall of Wave-Particle Duality as the central doctrine of quantum mechanics, from the viewpoint of the 2024 centennial of the matter wave. This is contrasted with the recent New Quantum Paradigm, in which there are no point particles or entangled probability waves, and classical trajectories follow directly from coherent quantum dynamics.

Introduction

This year, 2024, is the centennial of the matter wave. First derived by Louis de Broglie in his Ph.D. thesis in 1924, its key role in initiating the Quantum Revolution was quickly recognized by awarding de Broglie the Nobel Prize in Physics in 1929. Unfortunately, the physical nature of the matter wave was obscured by the assertion that it consisted of *both* a point particle of mass m and a distributed field with wavelength $\lambda = h/mv$ (h = Planck's constant and v is the velocity of the particle). This confusion was incorporated into the foundations of quantum mechanics and codified as "Wave-Particle Duality", whereby according to the established "Copenhagen interpretation", a probability wave governed the motion of the point particle. This duality was further compounded by a dichotomy between entangled coherent quantum waves on the one hand, and an incoherent classical world on the other.

In the past decade a new quantum interpretation without Wave-Particle Duality has received increasing attention as the resolution to the quantum paradoxes that were present for almost a century. The New Quantum Paradigm (NQP, Kadin 2011) is simpler, more logically consistent, and less abstract than the orthodox Copenhagen interpretation. In the NQP, a matter wave is a real coherent rotation of a fundamental vector quantum field, such as an electron or a quark (see Fig. 1). There are no point particles or probability waves; both particle trajectories and particle discreteness follow from the dynamics of the quantum field. Quantum measurements are simply quantum transitions between coherent quantum states of a measuring instrument. There is no quantum entanglement between distant quantum states, and no instantaneous action-at-a-distance. Finally, a composite of such fundamental fields, such as a neutron or an atom, is not itself a quantum wave, but rather acts like a particle. These paradigm shifts complete the earlier Quantum Revolution, but the NQP has been strongly resisted by much of the theoretical physics establishment, as indeed was the case for earlier scientific revolutions (Kuhn 1970).

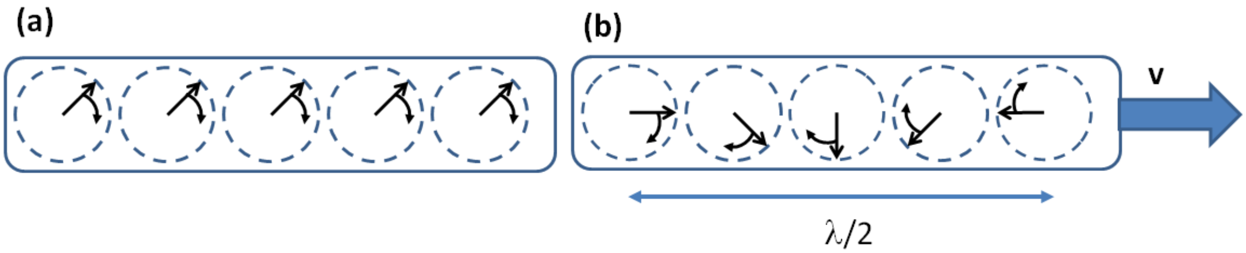

Fig. 1. Real-space picture of distributed electron wave in New Quantum Paradigm (NQP). There is no point particle; mass m, energy E, momentum p , and spin S are all associated with this rotating vector field. (a) Electron field rotating at frequency $f = mc^2/h$*, with uniform phase angle* ϕ*, and total spin* $S = \hbar/2$ *perpendicular to the plane, corresponding to electron at rest. (b) Electron moving at velocity v, showing phase gradient* $d\phi/dx = p/\hbar$ *and de Broglie wavelength* $\lambda = h/p$ *from Lorentz transformation.*

History of Wave-Particle Duality

The paradoxes inherent in Wave-Particle Duality go back to the beginning of quantum theory in the early 20th century. The original fundamental particle was based on the classical concept of an "atom" (from the Greek for indivisible), but by this period it was known that an atom consisted of one or more electrons, combined with a nucleus consisting of one or more nucleons (protons and neutrons). So if an electron is truly a fundamental particle, it had to be a point particle, which clearly cannot be divided further. While a nucleon was initially believed to be a similar point particle, it was found later (by 1970) to consist of a bound state of three quarks, where then the quarks were point particles. Such elementary particles are characterized by quantization of spin (intrinsic angular momentum), among other properties. (As discussed later, quantization of spin is obtained within the NQP from spontaneous self-organization of a continuous quantum field, so that point particles are unnecessary.)

A classical particle follows a classical trajectory $x(t)$ in space, with a momentum $p(t)$, and a total energy E, which is a constant of motion even in the presence of a varying potential energy $V(x)$. The dynamics of such a particle follow from Newton's laws, but may also be expressed in terms of Hamilton's equations of motion. If E is a function $H(x,p)$, the Hamilton differential equations are given by $\mathrm{d}x/\mathrm{d}t = \partial H/\partial p$ and $\mathrm{d}p/\mathrm{d}t = -\,\partial H/\partial x$. Remarkably, these classical equations follow directly from the trajectory of a coherent quantum wave packet (or a composite containing such waves internally), with no reference to classical particles. So in the NQP, there is no separate macroscopic classical world; quantum coherence is the basis for classical behavior on both macroscopic and microscopic levels.

In order to understand how quantum mechanics got stuck in a rut for almost a century, it is useful to review how it got started (see Hoffman 1959). In 1900 Max Planck modeled thermal radiation by assuming that electromagnetic waves have discrete energies, $E = nhf$, where f is the frequency of the wave and n is an integer. In 1905, Albert Einstein, in addition to developing special relativity ($E = mc^2$, where c is the speed of light), also explained ultraviolet photoemission in atoms (the photoelectric effect) in terms of photons (effectively, atoms of light) with $E = hf = \hbar\omega$ (where $\omega = 2\pi f$ is the radian frequency and $\hbar = h/2\pi$ is known as h-bar). In 1913, Niels Bohr modeled atomic spectra by assuming that an electron in orbit around the nucleus has quantized angular momentum $L= n\hbar$, and changes its energy by emitting or absorbing a photon.

In his graduate work, de Broglie asked whether a photon could have a small non-zero mass that might account for quantization. Applying special relativity to this massive photon in its rest frame, he asserted that both $E = mc^2$ and $E = hf$. So one has an oscillation $\sin(2\pi ft)$, where $f = mc^2/h$. Now consider a standard Lorentz transformation to a reference frame (given by coordinates t' and x') moving with velocity v: $t \rightarrow \gamma(t'-vx'/c^2)$, where $\gamma = (1-v^2/c^2)^{-1/2}$ is the standard factor in relativity. The particle of mass m now has energy $E' = \gamma E$ and momentum $p = \gamma mv$. The oscillation becomes a wave $\sin[2\pi(f't'-x'/\lambda)] = \sin(\omega t-\mathrm{k}x)$, where $f' = \gamma f = E'/h$, $\lambda = c^2/\gamma fv = h/p$, and $k = 2\pi/\lambda$ is the wave vector. So a relativistic Doppler shift has turned an oscillation into a de Broglie matter wave. While this was initially derived for a massive photon (which was later dropped as inconsistent with experiments), this can equally apply to any other relativistic particle, such as an electron, if one assumes that $hf = mc^2$ also applies here. De Broglie went on to show that such an electron wave going around an atomic nucleus also accounted for $L = n\hbar$ in the Bohr atom. He further asserted that such a matter wave was always accompanied by a point particle of mass m, and thus Wave-Particle Duality was born. So while de Broglie initiated the Quantum Revolution, he was unable to complete it.

But what does the matter wave represent? The Copenhagen interpretation (due mostly to Bohr and Heisenberg) focused on the statistical character of a matter wave, interpreting it as a probability wave associated with the location of a point particle within the wave. This gave rise to the Heisenberg Uncertainty Principle, which is really just a mathematical identity about the size of a classical wave packet. This in turn led to an entire quantum philosophy based on indeterminacy on the microscopic level. In the NQP, the matter wave represents a real distributed wave of a primary field, not a probability distribution of point particles, which do not exist. While there is statistical uncertainty associated with quantum transitions, indeterminacy is not a central aspect.

The relativistic nature of matter waves was clear right at the beginning, but subsequently was often overlooked. Since ω and $\mathbf{k}$ Lorentz transform exactly like E and $\mathbf{p}$, $E = \hbar\omega$ and $\mathbf{p} = \hbar\mathbf{k}$ are valid in all reference frames. Substituting ω and $\mathbf{k}$ for E and $\mathbf{p}$ in Hamilton's classical equations enables them to apply directly to matter waves (see Technical Notes). Furthermore, angular momentum $\mathbf{L}$ is Lorentz-invariant, so that both orbital angular momentum and intrinsic spin angular momentum may be quantized to a constant value (in units of $\hbar$) in any reference frame. These relativistic matter waves provided the basis for all subsequent formulations of quantum mechanics, including the (non-relativistic) Schrödinger equation. But the wave in the Schrödinger equation is not the real physical oscillation, but rather a mathematical wave Ψ that is frequency-shifted to suppress the relativistic "carrier wave" $\sin(mc^2t/\hbar)$. This transformation from a real wave $F(x,t)$ to a complex wave $\Psi = \exp(imc^2t/\hbar)F$ contributed to the widespread belief that the matter wave was an abstract mathematical representation rather than a true physical wave in real space.

The earlier established evidence for Wave-Particle Duality for several quantum entities is summarized in Table I. Although orthodox Wave-Particle Duality asserted that all particles have both aspects, the evidence was not equally direct. The stronger direct evidence is indicated by bold italics, and the weaker inferred evidence is indicated by parentheses. Within the NQP, electrons and photons are waves, while neutrons and atoms are particles. The inferred evidence for particles in the former cases, and for waves in the latter cases, has alternative interpretations. More generally, the NQP asserts that only the fundamental quantum fields of the Standard Model of particle physics (electrons, muons, neutrinos, photons, quarks, gluons, Z and W bosons) are true quantum waves. All composites of these are effectively particles, composed of internally confined quantum waves. No Wave-Particle Duality is necessary.

Table I. Summary of Conventional Evidence for Wave-Particle Duality
(Stronger direct evidence indicated by bold italics; weaker inferred evidence by parentheses.)

Entity	**Evidence for Waves**	**Evidence for Particles**
Electron	***Standing waves, Directional orbitals***	(Quantized spin, mass, charge)
Photon	***EM Waves***	(Quantized spin, energy)
Atom	(Quantized vibrations in molecules)	***Fixed size in molecules & solids***
Neutron	(Crystal diffraction)	***Fixed size in collisions & nucleus***

It is also important to understand the more direct evidence for electron matter waves. A standing wave consists of a linear superposition of wave components in opposite directions, and exhibits spatial nodes and antinodes (corresponding to zero and maximum intensity, resp.), which represent a unique signature that cannot be simulated by particle motion; one does not have superposition of particles. The alignment of nodes of electron standing waves within a crystal lattice provides the basis for the energy gap in such a crystal. Similarly, a P_x orbital in an atom gains its fixed directional character from the superposition of two counter-rotating electron wave components. In the NQP, the corresponding wave superpositions are not present for molecular rotations, since the atoms are effectively particles following a classical trajectory, even if the energies are quantized.

Composites and Diffraction

Physicists applied the Schrödinger equation to a wide variety of phenomena of electrons in atoms, molecules, and solids, as well as composites such as atoms and nucleons. A composite has a well-defined size (determined by the confined waves of the internal components), and follows a classical trajectory, with internal oscillations at frequencies $f_i = E_i/h$ for each of the internal components. From Wave-Particle Duality, it was further believed that there should be an additional matter wave corresponding to the composite of mass M, with an oscillation at $f=Mc^2/h$. Since the total relativistic energy $Mc^2 = \Sigma E_i$, this would require an oscillation frequency that is the sum of the component frequencies f_i, which in turn would correspond to multiplying component waves. In the NQP, no such higher frequency oscillation or product state is present (see Fig. 2), with important implications (see Technical Notes).

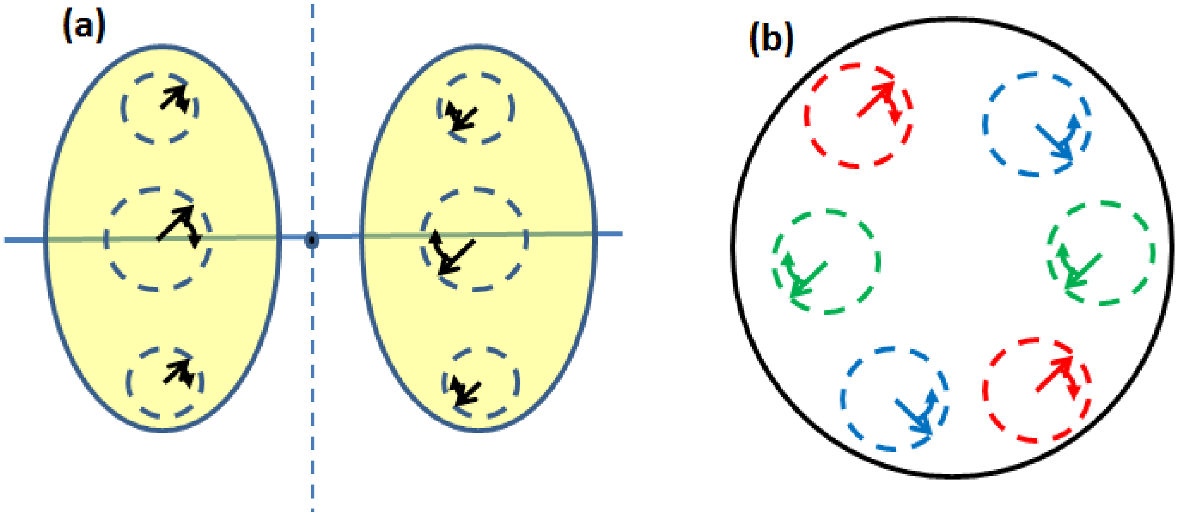

Fig. 2. Conceptual pictures of proton and hydrogen atom in NQP, showing internal wave structures of electron and quark components, but no oscillations corresponding to total proton mass or total atomic mass. (a) H-atom on Å scale, showing electron in P_x orbital, with two lobes of opposite phase angle ϕ due to standing wave superpositions, and nodal plane between lobes. (b) Proton on fm scale, showing three internal quark fields (uud), indicated by red, green, and blue rotating vector fields.

This two-tiered quantum picture in the NQP, with only the primary quantum fields being true waves, is logically quite consistent. So why were generations of physicists convinced otherwise? First, without a clear understanding of the nature of a matter wave, it was assumed to be universal, and applied to all particles. And certainly in the early years of the 20th century, the distinction between truly fundamental particles and composites (such as nucleons) was not understood. Second, quantized energies are not restricted to electrons in atoms; they also occur in molecular vibrations and rotations, and in nuclei, for example. Since quantized energies in the hydrogen atoms can be understood in terms of matter waves, it seemed logical to make the same argument for vibrating molecules. And third, and perhaps most compelling, was the case of crystal diffraction, which demanded a wave explanation for diffraction by beams of neutrons or atoms.

Consider first the case of molecular vibrations. From a classical point of view, these are effectively collective oscillations of masses connected by springs, at one or more characteristic frequencies f_i, so that each mass follows a trajectory $x(t) = A \sin(2\pi f_i t)$. Classically the amplitude A of such an oscillation can take any value, with energy $E \propto A^2$. But molecular vibrations exhibit a spectrum of discrete lines with energies $\Delta E = nhf_i$, so the oscillation amplitude must also be quantized. This is certainly non-classical, but matter is built up of quantized electrons and mediated by quantized photons. In the NQP, the molecular trajectories are classical, but the transitions between states of different amplitudes are true quantum transitions. So any oscillating trajectory at a frequency f will exhibit quantized energy with $\Delta E = hf$, on either the microscopic or macroscopic scales. The reason we generally don't notice this on the macroscopic scale is that the discrete energy separation is so small, typically less than thermal energies. Similarly, a phonon (a vibrational quantum in a solid) is conventionally treated as if it were a quantum particle like the photon, with energy $E = \hbar\omega$ and momentum $p = \hbar k$, moving with the speed of sound rather than the speed of light. But in the NQP, a phonon really represents a quantum transition between two amplitudes of a given quasi-classical vibrational mode in a crystal.

Consider now the important phenomenon of crystal diffraction, which was widely used (incorrectly, as it turned out) to prove the wave nature of a wide range of quantum particles. Diffraction off periodic structures was well established in the 19th century for classical electromagnetic waves, for wavelength λ comparable to the periodicity d, following the standard diffraction formula $n\lambda = 2d \sin\theta$, where θ is the angular shift of the diffracted beam. An equivalent formulation is expressed in terms of the wave vectors $\mathbf{k}_\mathrm{i}$ and $\mathbf{k}_\mathrm{d}$ of the incident and diffracted waves (where $|\mathbf{k}| = 2\pi/\lambda$) and the reciprocal lattice vectors $\mathbf{G}$ of the crystal ($|\mathbf{G}| = 2\pi/d$), essentially the peaks of three-dimensional Fourier transform of the spatial distribution of the crystal: $\Delta\mathbf{k} = \mathbf{k}_\mathrm{d} - \mathbf{k}_\mathrm{i} = \mathbf{G}$. This analysis assumes that the incident wave is coherent over a distance much larger than the periodicity d. X-ray diffraction from periodic crystal lattices was first observed in 1912, and established that x-rays are electromagnetic waves with wavelengths on the atomic scale. In 1927, diffraction using an electron beam was seen and used to confirm the existence of matter waves that de Broglie had proposed only a few years before. Atom diffraction was observed in 1930, and neutron diffraction in 1945. These all seemed to confirm that matter waves were universal, and that every particle of matter is accompanied by an extended coherent wave, *i.e.*, the doctrine of Wave-Particle Duality.

However, there is an alternative explanation of crystal diffraction that does not require waves at all. This considers the quantized momentum transfer $\Delta\mathbf{p}$ between an incident particle and a periodic quantum crystal, as illustrated for neutron diffraction in Fig. 3. Very early, Duane showed (1923) that such a spatially periodic crystal is limited to momentum transfers $\Delta\mathbf{p} = \hbar\mathbf{G}$, directly analogous to quantized energy transfer $\Delta E = \hbar\omega$ to a quantum state that oscillates in time. This was applied to the case of x-ray diffraction, but this analysis was subsequently forgotten. It was rediscovered many years later by Van Vliet (1967, 2010), who derived it using more modern quantum formalism, but this, too, was ignored. The key point is that instead of a matter wave diffracting from a classical crystal, one has a particle inducing a transition in a periodic quantum structure. This can also be understood in terms of phonons in the crystal; a diffraction event represents excitation of a (degenerate) phonon with $E = 0$ and $\mathbf{p} = \hbar\mathbf{G}$, which is an allowed quantum transition.

This analysis can be generalized beyond crystal diffraction to include diffraction from one or more orifices, or interference of two or more beams. For example, experiments showed single-orifice diffraction of a molecular beam of fullerene C_{60} to prove that this large molecule (molecular weight 721) exhibited a matter wave corresponding to the total mass (Arndt 1999). And experiments using a single-crystal neutron interferometer also showed the expected two-beam interference results (Rauch 1986). But from the perspective of the NQP, these experiments actually proved nothing about matter waves of the beam, but rather about the spatial Fourier transform of the measuring device, which restricted the momentum transfer in the measurement. In all these cases, *the quantum nature of the measurement simulated a wave nature for the beam*. This is a remarkable conclusion, and went sharply against the prevailing wisdom when it was first proposed.

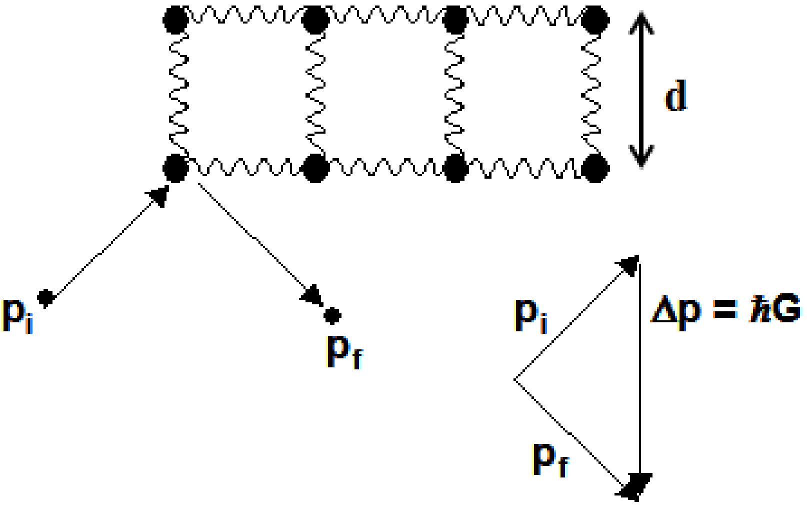

Fig. 3. Neutron diffraction from crystal in NQP, without neutron waves. Each neutron in a beam scatters from a single nucleus in a lattice, without net nuclear recoil, but with quantized momentum transfer absorbed by the entire crystal $\Delta\mathbf{p} = \hbar\mathbf{G} = h/d$. *Equivalent to excitation of phonon with* $\mathbf{p} = \hbar\mathbf{G}$ *and* $E = 0$. *Observation of neutron diffraction does <u>not</u> prove that the neutron is a matter wave.*

Quantum Measurement and Quantum Entanglement

A related paradox within the Copenhagen picture was presented by Schrödinger in 1935. In a gedanken-experiment (no animals endangered in this experiment!), Schrödinger asked how one would represent the state of a cat that would automatically be poisoned if and when a radioactive atom decayed. Would this “Schrödinger’s cat” be in a linear superposition of being alive and being dead, at least until it was observed by an external observer? Schrödinger presented this to demonstrate that the Copenhagen interpretation made no sense, although subsequently others took him seriously. But within the NQP, Schrödinger was right in his discomfort. It makes no sense to consider superpositions of anything but primary quantum fields. There is still statistical uncertainty in the state of the cat, but that uncertainty does not change the physical state of the cat, which follows the actual radioactive decay.

This also relates to the more general subject of quantum measurement. In the Copenhagen interpretation, a classical measuring instrument or observer is needed to force an indeterminate quantum state into one of the alternative results (or eigenstates) of the measurement. This transition was believed to be virtually instantaneous. In contrast, in the NQP, any measurement is a true quantum transition of the measuring instrument, with dynamics and timing appropriate to the interaction giving rise to this measurement. No separate classical observer is necessary.

Some of the most confusing and paradoxical aspects of the Copenhagen interpretation relate to quantum entanglement, which asserts that two or more interacting coherent quantum states remain coupled even after they move far apart. This correlation continues until a measurement or other interaction leads to “decoherence”, at which time the states decouple, apparently instantaneously changing their physical state. This action-at-a-distance would appear to violate “local reality” which is at the heart of special relativity (which in turn is at the heart of quantum mechanics). This entanglement provided the basis for a key criticism of the Copenhagen interpretation of quantum mechanics by Einstein and colleagues in 1935 (the EPR paradox). Einstein believed that this paradox showed that quantum mechanics was inconsistent or incomplete. But in later years, quantum entanglement and its associated nonlocality became widely accepted as a fundamental property of quantum mechanics. Furthermore, several experiments involving polarized photons were interpreted to prove the existence of entangled photon states (Zeilinger 1999), although these experiments may have alternative interpretations (see Technical Notes). There were even extensive research efforts to harness quantum entanglement for technological applications (not yet realized) in computing and communication.

Within the Copenhagen picture, entangled states are generated using abstract formalism based on product states, in a way that hides their nonlocality. In contrast, the NQP starts with real relativistic waves in real space, which are automatically consistent with local reality, and builds up from there. Electron states that overlap may interact quite strongly – this is the basis for the Pauli exclusion principle. But once they separate in space, their only interactions are via long-range electromagnetic potentials. There are no product states, and quantum entanglement is impossible. Einstein was right all along.

More generally, the Copenhagen interpretation required a transition from an indeterminate, coherent quantum microworld to a deterministic classical macroworld, enabled by decoherence of entangled quantum states. In the NQP, in contrast, classical trajectories follow directly from coherent quantum oscillators on the microscopic level, and quantum transitions between quantized levels are present at all levels. No decoherence is needed to recover classical behavior.

Quantized Spin and Coherent Quantum Domains

In understanding how a distributed wave can maintain the particle property of indivisibility, it is important to appreciate the central role of spin. Within the Copenhagen interpretation, spin is a mysterious quantized angular momentum associated with a point particle. But it is difficult to see how a point singularity can have an angular momentum. In contrast, it is easy to obtain angular momentum from a distributed wave (see Kadin 2005, Ohanian 1986). For example, consider a simple wave picture for a photon based on a propagating electromagnetic wave packet. Such a wave consists of oscillating **E** and **H** fields, perpendicular to each other and to the direction of motion. It is well known from the classical Maxwell's equations that the energy density in the wave can be expressed as $\mathcal{E} = |\mathbf{E} \text{ x } \mathbf{H}|$, and the momentum density as $\mathcal{P} = |\mathbf{E} \text{ x } \mathbf{H}|/c$. It is less well known, but still a standard result, that a classical electromagnetic wave can also carry angular momentum. In particular, consider a circularly polarized wave, which corresponds to rotation of fixed-length vectors **E** and **H** at angular frequency ω. In this case, one has an angular momentum density that can be expressed as $\mathcal{S} = |\mathbf{E} \text{ x } \mathbf{H}|/\omega$. (A linearly polarized wave does not carry angular momentum.) So $\mathcal{E} = \mathcal{S}\omega$, and if we assume a wave packet with total volume V such that $S = \int \mathcal{S}\, dV = \hbar$, then $E = \hbar\omega$ follows immediately (as does $\mathbf{p}=\hbar\mathbf{k}$ from relativity). In fact, a single photon is known to have $S = \hbar$, so this is quite consistent. This provides a simple physical picture of a photon as a relativistic wave packet with quantized spin; no point particle is needed. A similar argument can be applied to all other fundamental quantum fields; they all have quantized spin and correspond to rotating vector fields. The only difference is that for particles with nonzero mass, one can transform to the rest frame, with a rotation frequency $f = mc^2/h$. This is the key physical picture of the NQP; matter consists of spatially localized coherently rotating relativistic vector fields, each rotating at its characteristic frequency. The integrity of a given "particle" is associated with quantization of spin. Since spin is Lorentz-invariant, so is the particle itself.

Of course, such a simple picture immediately brings up another key question: Why can't one cut a photon or an electron in half? In order to avoid this, a local nonlinear self-interaction is needed that acts both to maintain phase coherence and to quantize the total spin (Kadin 2006). One can imagine a disorganized soup of quantum fluctuations that spontaneously self-organizes into localized domains, each with coherent rotations and fixed spin. This is analogous to the self-organization of magnetic domains below the Curie temperature, where each domain acts like a macroscopic magnetic particle, even though it is composed of a large number of interacting atomic spins. For electrons, there is the additional constraint imposed by the Pauli exclusion principle, that no two electrons in the same location may have the same frequency and spin. In other words, the amplitude of the coherent electron field is constrained. The Pauli principle represents a real physical interaction that is built into the self-interaction of the electron quantum field. In contrast, the photon is not subject to the Pauli principle, so that its self-interaction does not reflect such a constraint.

In the years since the NQP was first proposed, several mathematical approaches to quantizing field self-interactions have been proposed, and this is still a subject of current research. There is insufficient space here to review them. However, a common aspect is that the self-interaction mechanism is hidden while quantum waves are coherent, but comes into play whenever there is a quantum transition that would lead to reconfiguration of the field. Furthermore, some of these approaches also incorporate a mechanism for generating mass, *i.e.* the characteristic frequency of a given quantum field. This is analogous to the Higgs mechanism that was earlier proposed for mass generation within the Standard Model of particle physics. However, as a spin-zero particle, the original proposed Higgs particle was incompatible with the rotating vector fields of the NQP. The difficulties in observing this original Higgs particle led in recent years to a re-examination of the mass generation problem.

Conclusions

This review has chronicled the rise and fall of Wave-Particle Duality and the associated Copenhagen Interpretation of quantum mechanics. Wave-Particle Duality arose in the early 20th century as a desperate attempt to make sense out of a fundamentally inconsistent set of classical pictures. But ultimately, Wave-Particle Duality was brought down by unresolvable inconsistencies and paradoxes. The New Quantum Paradigm (NQP) avoids these paradoxes, preserves most of the mathematical formalism, and presents a clear physical picture of how the microworld and the macroworld are related. This paradigm shift represents the completion of the Quantum Revolution that began in the early 20th century, but was stalled for almost 100 years.

However, the extent to which Wave-Particle Duality remained a core belief among several generations of physicists is truly remarkable, especially in retrospect. There is very little in the NQP that could not have been proposed any time in the past century, and indeed the shortcomings of Wave-Particle Duality were identified repeatedly. But even now, many senior physicists refuse to consider that Wave-Particle Duality may be wrong. The field of quantum mechanics bifurcated long ago into two parts: a highly successful calculational tool on the one hand, and a paradoxical set of foundations on the other. Generations of physicists have been educated to ignore physical intuition about the paradoxes, while focusing on mathematics divorced from physical pictures. In response, the field of theoretical physics became more mathematically abstract, straying far from its origins explaining the behavior of real objects moving in real space. Now that the Quantum Revolution has finally been completed, this should place physics back on track for future insights into the fundamental behavior and origins of the physical universe.

References

M. **Arndt**, *et al.* (1999), "Wave-particle duality of C60 molecules", *Nature*, vol. 401, p. 680.

Louis **de Broglie** (1923), "Waves and Quanta", *Nature*, vol. 112, no. 2815, p. 540.

Louis **de Broglie** (1924), "Recherches sur la Theorie de Quanta", Ph.D. Thesis, Univ. Paris, English translation of Chap. 1 in "Phase Waves of de Broglie", *Am. J. Phys.*, vol. 40, p. 1315 (1972).

Louis **de Broglie** (1929), "The Wave Nature of the Electron", Nobel Prize Lecture, available at http://www.nobelprize.org/nobel_prizes/physics/laureates/1929/broglie-lecture.pdf

William **Duane** (1923), "The transfer in quanta of radiation momentum to matter", *Proc. Nat. Acad. Sci.*, vol. 9, p. 158. Available at http://www.pnas.org/content/9/5/158.full.pdf.

A. **Einstein**, B. Podolsky, and N. Rosen (1935), "Can quantum mechanical description of physical reality be considered complete?", *Phys. Rev.* vol. 47, p. 777.

Banesh **Hoffman** (1959), *The Strange Story of the Quantum*, Dover Publications.

A.M. **Kadin** (2011), "Waves, particles and quantized transitions: A new realistic model of the microworld", http://arxiv.org/abs/1107.5794.

A.M. **Kadin** (2009), "Superconductivity without Cooper Pairs?", http://arxiv.org/abs/0909.2901.

A.M. **Kadin** (2006), "Wave-Particle Duality and the Quantum Domain Picture", http://arxiv.org/abs/quant-ph/0603070.

A.M. **Kadin** (2005), "Circular polarization and quantum spin: a unified real-space picture of photons and electrons", http://arxiv.org/abs/quant-ph/0508064.

Thomas S. **Kuhn** (1970), *The Structure of Scientific Revolutions*, 2nd Ed., Univ. of Chicago Press.

H.C. **Ohanian** (1986), "What is Spin?", *Am. J. Phys.*, vol. 54, p. 500.

H. **Rauch** (1986), "Neutron interferometric tests of quantum mechanics", *Contemp. Phys.*, vol. 27, p. 345.

Erwin **Schrödinger** (1935), "Die gegenwartigen Situation in der Quantenmechanik", *Naturwiss.* vol. 23, p. 807, English translation in "The Present Situation in Quantum Mechanics: A Translation of Schrödinger's Cat Paradox Paper", *Proc. Am. Phil. Soc.*, vol. 124, p. 133 (1980).

K.M. **Van Vliet** (1967), "Linear momentum quantization in periodic structures", *Physica*, vol. 35, p. 97.

C.M. **Van Vliet** (2010), "Linear momentum quantization in periodic structures II", *Physica A*, vol. 389, p. 1585.

A. **Zeilinger** (1999), "Experiment and the Foundations of Quantum Physics", *Rev. Mod. Phys.*, vol. 71, p. S288.

Technical Notes

Further analysis is presented here of two important topics addressed in this Essay.

I. Classical Hamiltonian Trajectory Derives from Coherent Quantum Oscillations

First, let us review a classical particle trajectory $x(t)$, given by an energy functional $E = H(p,x)$, where the total energy E is a constant of the motion along the trajectory and p is the momentum. So we have

$$\frac{dE}{dt} = 0 = \frac{\partial H}{\partial x}\frac{dx}{dt} + \frac{\partial H}{\partial p}\frac{dp}{dt}$$

which rearranges to yield

$$\frac{dp}{dt} = -\frac{\partial H}{\partial x}\left(\frac{dx}{dt} \Big/ \frac{\partial H}{\partial p}\right)$$

So the two Hamilton equations of motion are linked:

$$\frac{dx}{dt} = \frac{\partial H}{\partial p} \Leftrightarrow \frac{dp}{dt} = -\frac{\partial H}{\partial x}$$

Relativistically, the rest energy E_0 of a particle moving in a potential $V(x)$ (where m_0 is the rest mass when V=0) is given by $E_0 = mc^2 = m_0c^2 + V(x)$. In a reference frame moving with velocity v, the energy and momentum are given by $E = \gamma E_0$, $p = \gamma mv$, where $\gamma = (1-v^2/c^2)^{-1/2}$. These are equivalent to the usual relation $E = [E_0^2 + (pc)^2]^{1/2} = [(m_0c^2+V)^2 + (pc)^2]^{1/2}$, which in turn yields the Hamilton equations $\partial H/\partial p = pc^2/E = v = \mathrm{d}x/\mathrm{d}t$ and $\partial H/\partial \mathrm{x} = (1/\gamma)\,\partial V/\partial x = -\mathrm{d}p/\mathrm{d}t$.

These are exactly the same formulas for the motion of a localized oscillator that represents a quantum wave packet or a confined standing wave, with a centered trajectory $x(t)$, with wave parameters ω and k, and $\omega = H(k,x)$ is a constant of motion. The dispersion relation for such a relativistic wave is given by $\omega = [\omega_1^2 + (kc)^2]^{1/2} = [(\omega_0+u)^2 + (kc)^2]^{1/2}$, where ω_0 is the rest-frame frequency of the oscillator and ω_1 its shifted frequency in the presence of a potential $u(x)$. This yields the Hamiltonian equations $\partial\omega/\partial k = kc^2/\omega = v = \mathrm{d}x/\mathrm{d}t$ (also the group velocity of the wave packet) and $\partial\omega/\partial \mathrm{x} = (1/\gamma)\,\partial u/\partial x = -\mathrm{d}k/\mathrm{d}t$. With the usual association $E = \hbar\omega$ (which derives from quantization of spin), together with $p=\hbar k$ and $V = \hbar u$, the classical particle trajectory follows immediately; classical energy and momentum are concepts derived from quantum waves. Furthermore, in a composite of multiple quantum waves bound together (such as a nucleon or an atom), the same classical trajectory follows from each of the confined oscillators, even though each is oscillating (or rotating) at its own characteristic frequency.

Fourier transforming this relativistic dispersion relation leads to the Klein-Gordon wave equation for a real field $F(x,t)$:

$$\frac{\partial^2 F}{\partial t^2} = c^2\frac{\partial^2 F}{\partial x^2} - [\omega_0 + u(x)]F$$

While this is a scalar wave equation, it can easily be generalized for a rotating vector field, *i.e.*, a circularly polarized wave carrying spin. It can also be frequency shifted, subtracting off ω_0, by substituting $F = \Psi e^{-i\omega t}$. This is directly analogous to down-converting a narrowband radio signal, suppressing the high-frequency carrier to extract the information. Dropping higher-order terms for the non-relativistic limit,

$$-2i\omega_0 \frac{\partial \Psi}{\partial t} = c^2 \frac{\partial^2 \Psi}{\partial x^2} - 2\omega_0 u \Psi$$

which becomes the standard Schrödinger equation:

$$i\hbar \frac{\partial \Psi}{\partial t} = -\frac{\hbar^2}{2m} \frac{\partial^2 \Psi}{\partial x^2} + V\Psi$$

Note that c has dropped out, hiding its relativistic origins.

II. More Implications of the Lack of Composite Quantum Waves

As discussed in the Essay, the doctrine of Wave-Particle Duality was earlier applied equally to both fundamental and composite particles, even though they are quite different. Fundamental particles have two classes: fermions with spin $\hbar/2$ and bosons with spin $\hbar$. Fermions (electron, muon, neutrino, quark) are subject to the Pauli exclusion principle, preventing occupation by two or more identical particles. Bosons (photon, gluon, W and Z_0) are not subject to Pauli principle limitations. In the old orthodox quantum picture, composite particles were asserted to be either bosons or fermions depending on whether the total angular momentum of the components was half-integral (fermion) or integral (boson). So a neutron or proton (spin $\hbar/2$) was a fermion, while a helium-4 atom (spin 0) was a boson. These associations were used to explain the properties of a wide variety of physical systems. For example, the incompressibility of neutron stars was believed to be due to the Pauli exclusion principle applied to neutrons. The low-temperature superfluidity of liquid helium was believed to be based on a quantum ground state associated with boson condensation of He-4 atoms, and superconductivity was based on the formation of bound pairs of electrons (Cooper pairs) with spin 0 that were effectively bosons.

However, in the NQP, such composites are all effectively particles, with neither boson nor fermion character, and are not subject to linear superposition. So a very different explanation is needed for these established phenomena. The incompressibility of neutron stars may be attrributed to the fermionic nature of the internal quarks. Superconductivity and superfluidity may alternatively be attributed to two-phase packing of valence electrons (Kadin 2009).

The absence of composite quantum waves and associated product states also eliminates quantum entanglement of initially interacting quantum waves. However, in earlier years substantial experimental evidence for quantum entanglement was obtained, based on optical experiments involving linearly polarized single photons. But within the NQP, a single photon with $S = \hbar$ is a rotating vector field that is always circularly polarized. In contrast, a linearly polarized electromagnetic field carries no angular momentum. One may construct a linearly polarized electromagnetic field from a linear superposition of two photons with opposite helicities, but this is not a single-photon state. It has been suggested that these experiments are measuring such photon pairs but attributing them to single photons, in a way that simulates quantum entanglement. The full resolution of this paradox remains a subject of current investigation.