# Solving the mystery of wave/particle duality—the road to a unified theory of physics

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**Abstract**

The mystery of wave/particle duality persists because of the stubborn adherence to the point-particle model of elementary particles. This has excluded a whole class of theories based on a three-dimensional extended wave model. It is this class of theories which holds the promise of giving both an intuitively obvious resolution to the mystery of wave/particle duality and the key to the unification of the fundamental forces. It has been incredibly difficult, however, to construct a wave model that is consistent with the observed behavior of the objects we call elementary particles. We present here a new wave model which holds the promise of being just such a consistent model. This model gives an intuitively obvious explanation of wave/particle duality. Furthermore, this model opens up a new path in the search for a unified theory of elementary particles and the fundamental forces.

## 1 Introduction: the mystery of wave/particle duality

In a now-classic quote, Richard Feynman described wave-particle duality as "the only mystery of quantum mechanics." It is, indeed, a mystery when you picture elementary particles using the point particle model. In classical physics all of the objects of nature were divided into two categories, particles and waves. Matter was understood to be made of discrete particles while light, for example, was understood to be purely a wave phenomenon. The quantum revolution blurred the boundaries between these two categories and eventually merged them into a single category of wave/particles (or particle/waves or "wavicles" - the awkward nomenclature reflects our lack of understanding of what these things really are). Nevertheless, the particle concept continues to dominate our thinking about the nature of elementary particles. The current state of understanding of fundamental particles is that particles exist but somehow (mysteriously) have wave properties associated with them. This approach leads to the many mysteries of quantum theory (and, incidentally, also relativity theory) which to this day remain unresolved. The classical concepts are clearly inadequate here because the fundamental properties of particles and waves appear to be mutually exclusive. No one has yet been able to answer the question "How can a particle have wave-like properties?".

This question subtly maintains the dominance of the particle aspect of matter, in spite of the fact that the wave nature of matter has been recognized and widely accepted for the past eighty years. Louis de Broglie introduced his matter wave hypothesis in 1924, and soon thereafter Davisson and Germer confirmed the wave behavior of matter by observing diffraction in the scattering of electrons from a metal surface. But the mathematical formalism of quantum mechanics simply appended this wave behavior of matter to the familiar particle properties of matter. The particle concept continued to play the central role.

Wave interference is a wave disturbance in an extended medium and this is the antithesis of a point particle model. There are strong reasons, however, for believing that the wave properties of matter are more fundamental than the particle properties. To solve the mystery of wave-particle duality we need an extended wave-like model of elementary particles. But developing such a model has proven to be exceedingly difficult. The dominance of the particle concept on our thinking has been a subtle but insurmountable barrier. But if we turn around the logic of the first paragraph and instead say that waves exist and that somehow (not so mysteriously) they have particle properties associated with them, the whole situation becomes much clearer. In the language of wave-particle duality, we are in effect turning around the question asked above to read "How can a wave have particle-like properties?"

## 2 Models of the electron

The electron is perhaps the simplest of the elementary particles and has been studied extensively. We know a great deal about its properties and yet, in spite of this, we still do not have a fully consistent model of its internal structure. The commonly accepted "working model" of the electron is that it is a point particle. But the point particle model does not easily account for properties such as intrinsic spin angular momentum which seem to require a finite size. And in a broader context, the point particle model does not account for relativistic behavior (such as the maximum speed being the speed of light) or its quantum mechanical wave behavior in a natural way. These behaviors are simply posited as the way the electron behaves in order to be consistent with experimental observations. In quantum field theory the point particle model leads to the well-known problem of infinities. Quantities such as mass and charge, which experimentally have finite values, are found instead to have infinite values. While the mathematical technique of renormalization gets around these infinities by subtracting them off leaving a finite result, the appearance of these unphysical infinite values is nevertheless troublesome. Clearly, a model of the electron which is finite in size and also accounts for the relativistic and quantum mechanical wave behavior in a natural way would be preferable.

Many attempts have been made to construct a model of the electron with finite size, but all have failed for various reasons. The most common error has been to attribute properties such as mass and electric charge that apply to the electron as a whole to the internal "parts" of the electron. This was one of the problems with the Lorentz theory of the electron which modeled the electron as a sphere with electric charge distributed throughout it. But according to J. J. Thomson, the energy contained in the field of a spherical charge of radius $a$ is proportional to $e^2/2a$, which diverges as the radius goes to zero. Thus the only apparent choices are a point particle with infinite energy or a particle of finite radius which is unstable because of the Coulomb repulsion between its various parts. Neither of these alternatives is acceptable. Furthermore, models that picture the electron as a rigid sphere of finite radius are inconsistent with relativity theory. To move as a rigid sphere, interactions with external sources must travel through the sphere instantaneously, contrary to relativity theory that imposes the speed of light as the speed limit for the propagation of such interactions. And just like the point particle model, the rigid sphere model does not account for relativistic behavior or the wave behavior of matter.

Other models have been presented, but it is not our purpose here to present a detailed history of them. Because of the failures to construct a finite model of the electron, the point model was adopted by the physics community as the "lesser of the evils." Its use has led to significant progress in our understanding of the elementary particles and their interactions, but the resulting theory, quantum field theory, should be considered an effective theory that is not yet a complete theory of matter and its interactions.

More recently, string theory has proposed replacing point particles with one-dimensional vibrating strings. This approach eliminates the problem of infinities but at the expense of introducing extra spatial dimensions and higher dimensional objects called D-branes for which there is no experimental evidence. While string theory is an intriguing idea, it is still speculative and should not be considered as the only alternative to point particles.

The problem of understanding the internal structure of the elementary particles (and of eliminating the unphysical infinities of quantum field theory) remains to be solved. The key to solving this problem—that is, the key to constructing a consistent model of the electron—is to take its wave nature seriously, more seriously even than its particle nature.

## 3 Of electrons and lightwaves - what's waving?

If we are to take the wave behavior of matter as fundamental, we first need to answer the question "waves of what?". The accepted interpretation of de Broglie waves as "probability waves" does not give us a physical picture of what's waving, only an abstract mathematical formalism. Somewhat more subtly, the interpretation of lightwaves as waves in the electromagnetic field, though seemingly more physical than probability waves, is not at a level appropriate for understanding the internal structure of the electron.

To begin our investigation of fundamental concepts we must first examine what we mean by the words "particle" and "wave". That is, we must critically examine the properties that we associate with each of these concepts. To make the discussion more concrete we select a representative from each category, say the electron as a representative particle and light as a representative wave.

The primary property of a particle such as an electron is that it is localized. It literally has a *location*. I can identify its location and say that it is "right here." This is not to be confused with the uncertainty in an electron's location that quantum theory describes. This is a secondary issue related to the limitations of the classical particle concept, but for now we simply recognize that an electron can be confined within a small volume so that we can say for instance that an electron is attached to a particular atom.

Light, on the other hand, is not confined. It travels freely as a wave with a well-defined wave speed. All lightwaves travel at the same speed in vacuum, the speed of light, $c = 3.0 \times 10^8$m/s. A free electron, on the other hand, can move with any speed ranging from zero up to the maximum speed limit imposed by nature, the speed of light. Here we bump headlong into one of nature's deep mysteries. Why is it that an electron should have the speed of light, a *wave speed*, as its upper limit? While this connection between particles and lightwaves is universally recognized, the implications of it are not. Relativity theory offers only a mathematical justification based on mathematical consistency. It shows us that if particles with non-zero rest mass travel at speeds greater than the speed of light, the consequences violate certain basic laws of physics. For this reason we accept the speed limit nature imposes on particle motion. But relativity theory does not give us a *physical* explanation of why particles and light share this common speed. This common speed suggests an intimate connection between electrons (particles) and light (waves).

Applying Occam's razor, when two objects share a common property it is simpler (and therefore preferred) to consider them as two aspects of the same thing instead of assuming that they are two fundamentally different things that just coincidentally happen to share this property. Such coincidences seldom if ever occur in nature. Instead they usually point to an underlying connection. This leads us to our first major conclusion, that electrons and light are two aspects (perhaps two *manifestations* is better) of the same thing. Indeed, if particles and light really are two manifestations of the same thing, we should expect to see transformations from one to the other in nature. Do we see these transformations? Of course we do! They are called particle creation (particles from light) and particle annihilation (light from particles). But what is the "thing" that electrons and light are made of? To answer this question, we take a "divide and conquer" approach and first ask the more limited question "What is light made of?"

What is the medium through which light waves propagate? This question has perplexed physicists since the begining of the nineteenth century when Thomas Young first demonstrated that light is a wave phenomenon. Light seems to have no difficulty propagating through empty space from one end of the universe to the other, so whatever the medium is, it must pervade the entire universe. This idea led to the theory of the luminiferous æther which was very popular during much of the nineteenth century. The æther theory, however, proved untenable and was replaced by the more abstract theory of the electromagnetic field. This theory, first published by James Clerk Maxwell in 1873, is still the basis for our current understanding of light, and if you ask the average physicist on the street, "What's waving when a lightwave waves?" he is likely to answer, "the electromagnetic field." But this is not an acceptable answer because the electromagnetic field is a purely mathematical construction, not a physical medium. Light, on the other hand, is a physical phenomenon; it propagates through *physical* space, and logic therefore requires a *physical* medium to support these light waves. We are therefore confronted with the conundrum which has baffled physicists for two centuries, *how can light waves propagate through empty space?*

Think about this for a moment. Have we asked a question that has no answer? On the contrary, there is an answer which is so simple and so obvious that only our misconceptions of the nature of space have prevented us from seeing it. In essence, we have already stated the answer without realizing it. It is already evident in the statement of the conundrum above. We get our first glimpse of the answer by restating the conundrum as a statement rather than a question, *lightwaves propagate through empty space.* But for this to be an acceptable answer, we must understand more than the trivial statement that lightwaves travel from point A to point B, we must understand the method of propagation itself. To gain that understanding, we must examine our fundamental concepts of space itself.

From an operational point of view, space is a set of geometric relationships. The concepts of location, spatial order, and distance are integral parts of what we mean by space. We must be careful to distinguish between mathematical space, which we are free to construct in any way we want, and physical space, in which physical phenomena occur and whose properties can be determined experimentally. We are here considering only physical space. That physical space has physical reality is apparent from the concept of distance. A configuration consisting of two objects located one meter apart is distinguishable from another configuration consisting of the same objects located two meters apart, even though the only difference between the two configurations is the amount of "empty space" between them.

We are now in a position to draw two very important conclusions: (1) physical space is the "physical medium" through which lightwaves propagate, and (2) lightwaves are wave-like disturbances in the geometry of physical space. This gives us the following picture of a lightwave. As a lightwave passes through a region of space, the local geometry of that region of space is distorted from its normal Euclidean configuration into a (dynamic) non-Euclidean configuration. After the lightwave has passed by, the region of space returns to its quiescent Euclidean configuration. Shifting our emphasis from lightwaves to physical space, we can restate our important conclusion as: **physical space is a dynamic continuum which supports wave motion.**

The notion of a dynamic geometry of space is not new, of course. It is present in Einstein's general theory of relativity in which gravity waves are a wave-like disturbance in the geometry of space. But gravity waves, which are produced by large-scale motion of matter, are of a macroscopic nature. In contrast, the waves proposed here are waves in the geometry of space on a microscopic scale, produced by wave-like disturbances associated with the fundamental particles of nature.

## 4 Wave model of the electron

But if lightwaves are waves in the geometry of space and, as we have proposed, light and electrons are made of the same "stuff", then electrons must also be waves in the geometry of space. There is a natural tendency to use plane waves to describe wave motion whenever possible. Plane waves are simple and they are solutions of the linear wave equation, which allows one to build complicated wave motions using linear superposition. But plane waves are too simple to represent the physical

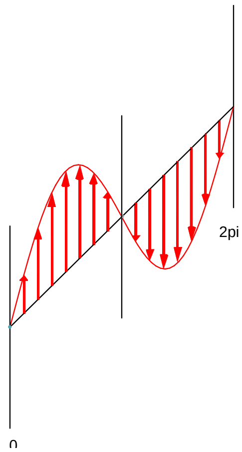


Figure 1: A linearly polarized wave.

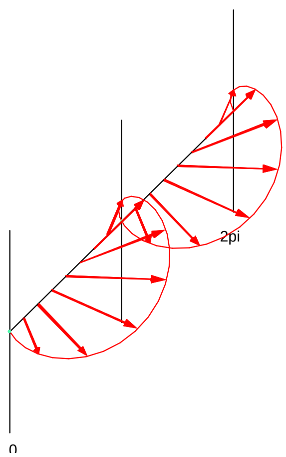


Figure 2: A circularly polarized wave, helicity = +1.

waves associated with elementary particles. First of all, a plane wave violates the principles of special relativity. Consider a wave traveling along the $x$ axis at the speed of light. As a point on the $x$ axis is displaced, it not only disturbs the adjacent points on the $x$ axis, contributing to the forward motion of the wave, but also disturbs the adjacent points in the $y$-$z$ plane. These disturbances must also travel outward at the speed of light, contrary to the simple plane wave model in which the entire $y$-$z$ plane moves in unison. For the $y$-$z$ plane to move in unison, the disturbance on the $x$ axis must be transmitted instantaneously to all points in the $y$-$z$ plane in violation of the principles of special relativity. Secondly, plane waves are too simple to account for the various properties of elementary particles.

Consider, for example, the puzzling nature of quantum mechanical spin. The point particle model does not easily account for spin, nor does a simple plain wave model. But, as we now show, the space wave model of elementary particles can account for spin in a very natural way if we put the right "twist" on the waves. For reference, we show in Fig. 1 a simple sine wave. What is shown in the figure is the displacement of points on the $x$ axis. It will be useful in what follows to remember that points off the $x$ axis will also be disturbed as discussed above, with this disturbance moving away from the $x$ axis at the speed of light. But to understand spin, we need only consider the

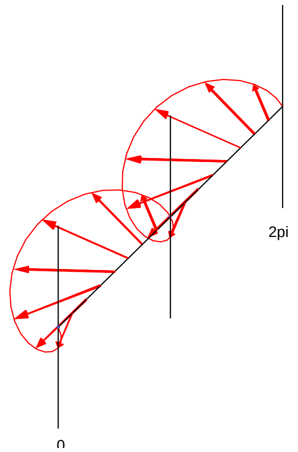


Figure 3: A circularly polarized wave, helicity = -1.

displacement along this reference line. Recall that photons only occur in right- and left-circularly polarized forms (spin $J = \pm 1$ in natural units)[4]. In terms of our wave model, we interpret this as a rotation of $2\pi$ of the plane of displacement for an advance of $2\pi$ in the phase of the wave. Fig. 2 shows the resulting wave motion for a right-hand rotation of the plane of displacement, and Fig. 3 shows the wave motion for a left-hand rotation. To help understand the behavior of these waves we make several observations. First, these waves differ in several ways from the usual representation of circularly polarized light which consists of the superposition of two plane waves differing in phase by a quarter wave. The waves we are considering are waves in space, not in the electromagnetic field. The displacement amplitude varies sinusoidally, whereas in circularly polarized light the amplitude is constant as the plane of polarization rotates. And most curiously, the displacement of the wave in Fig. 2 is always to the right of the $x$ axis while the displacement of the wave in Fig. 3 is always to the left. That is because when the displacement is negative, the displacement axis is rotated $\pi$ radians from the corresponding point of positive displacement. Secondly, although the wave motions shown in Figs. 2 and 3 are unusual, they do satisfy the linear wave equation and must therefore be considered as allowed wave modes. Thirdly, the superposition of the wave in Figs. 2 and 3 produce a plane-polarized wave, but with the curious feature that it repeats with a period of $\pi$ rather than $2\pi$. Finally, and most importantly, the peculiar behavior of the waves in Figs. 2 and 3 is key to understanding the electromagnetic interaction.

The wave motions in Figs. 2 and 3 are the building blocks for the simplest of elementary particles, the electron and the positron. To build these particles, these waves must be localized. To do that, we deform the path of the waves from the linear $x$ axis to a circular path in a way that satisfies periodic boundary conditions. Specifically, we match boundary conditions at zero and $\pi$ radians (*not* $2\pi$) noting that the waves in Figs. 2 and 3 repeat with a period of $\pi$. If we wrap the waves around to the left, the wave in Fig. 2 becomes a circulating wave with displacement only in the outward direction and the wave in Fig. 3 becomes a circulating wave with displacement only in the inward direction. These wave patterns maintain their stability through a nonlinear self-interaction. As the wave travels around its circular path, it sends a wave disturbance inward across the circle which interferes with the circulating wave on the opposite side of the circle producing self-interference. Mathematically, these wave patterns represent stable three-dimensional soliton solutions of an as-yet-unknown nonlinear wave equation.

The phenomenon of electric charge is associated with the direction (inward or outward) of the displacement of the circulating wave. An analysis of the helicity of these two waves shows that particles that are positively charged have wave displacements that oscillate in the outward direction

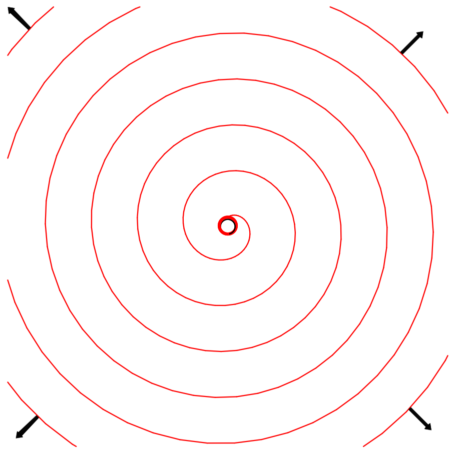

Figure 4: Ripples traveling outward from source.

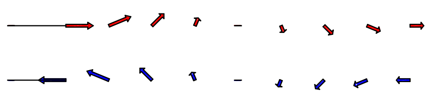

Figure 5: Details of electron (bottom) and positron (top) ripples traveling outward from sources (at left).

and negatively charged particles have wave displacements that oscillate in the inward direction. This appears to be the fundamental reason that there are two types of electric charge.

# 5 Wave model of the Coulomb force

Circulating waves naturally disturb the surrounding space and send out ripples, much as if you dip your finger into a pond and spin it around in circular motion. Fig. 4 shows the wave crest of these ripples spiraling outward from the source particle, represented by the small circle at the center. These wave crests travel outward at the speed of light. The sense of inward or outward oscillation continues out into the ripple field traveling outward from the circulating wave. A positron sends out ripples that have a net displacement pointing away from the source, while an electron sends out ripples with a net displacement pointing toward the source, as shown in Fig. 5. The circulating waves of these particles are viewed edge-on in this figure, with the lines at the left representing the diameters of the circulating wave patterns. The phase of the waves is chosen at the instant when the circulating waves have maximum amplitude at the right end of this diameter and zero amplitude

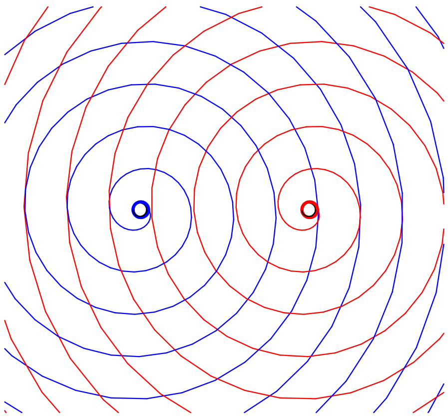

Figure 6: An electron and a positron in each other's ripple field.

at the left end. The sequence of displacement vectors moving to the right show representative displacement vectors of one cycle of ripples along one line directed radially outward from the source.

The component of the displacement perpendicular to the plane of circulation averages to zero over a full cycle, with the primary contribution to the interaction between particles resulting from the horizontal component only which, for a positron (upper sequence in Fig. 5) has a net outward displacement, while for an electron (lower sequence in Fig. 5) has a net inward displacement (averaged over a full cycle). Therefore, to understand the basics of particle-particle interaction in the wave model, it is sufficient to observe what is happening only in the plane of circulation. In the wave model of matter and interactions, the Coulomb interaction is a simple result of two circulating waves representing charged particles sitting in each other's ripple fields, as in Fig. 6. The Coulomb interaction is a result of wave interference between the (nonlinear) circulating wave and the (linear) waves of the ripple field. Because of the intrinsic nonlinearity of the soliton wave, the waves don't simply pass through each other unaltered. The soliton wave gets a little boost during each cycle of its circulation. If this ripple field is produced by a positron at the far left this motion will appear to be the result of an attractive force between the positron and the electron, while if it is produced by an electron at the far right it will appear to be the result of a repulsive force between the the two electrons. This phenomenon which is interpreted classically as the electric force is seen here to be a consequence of wave interference.

## 6 Unification of the fundamental forces

The wave theory of matter gives a simple explanation for the fundamental forces, including the long-range forces such as the Coulomb force. The circulating wave model of "particles" can account for all of the fundamental forces between particles simply in terms of wave interference.

• The *electric force* is a result of the motion of a circulating "charged particle" wave interfering with a background displacement wave that itself has a "charged particle" wave as its source. This wave interference causes the circulating wave to drift either toward or away from the source of the background wave depending on the direction (inward *vs.* outward) of the circulating wave and of the background displacement wave. It is the asymmetry (inward *vs.* outward) of the circulating waves of charged particles which leads to the dual nature (attractive *vs.* repulsive) of the electric force.

• The *magnetic force* is similar to the electric force in that it also is a result of the motion of a circulating "charged particle" wave interfering with a background displacement wave that itself has a "charged particle" wave as its source. But the effects attributed to the magnetic force are those that depend on the rotational aspect of the circulating particle and the background displacement wave. It is this rotational aspect which leads to the direction of the drift motion of the circulating wave (*i.e.*, the direction of the magnetic force) to be directed perpendicular to the line joining circulating wave and the source wave.

The unification of the electric force and the magnetic force becomes especially clear in the circulating wave model of matter. Both are aspects of the wave interference between a circulating wave and a background displacement wave, the electric force being related to the radial component of the waves and the magnetic force being related to the rotational component of the waves.

• The *gravitational force* results from the interference between circulating waves and background waves when one or both have "neutral" oscillations, i.e., displacement waves that oscillate both inward and outward about an equilibrium position. To first order, the interaction results in zero net motion of the particle, but a small effect results from the gradient of the background displacement field as the displacement wave from the source spreads out as it moves away from the source. This is a much smaller effect than the first order effect and offers a plausible explanation for why the gravitational force is so much weaker than the electric and magnetic forces.

• The *strong nuclear force* involves a direct overlap of the circulating displacement waves at close range. This is a nonlinear interaction between the waves which is much stronger than the linear interaction between circulating waves and the background displacement wave field that occurs at larger distances. And because this nonlinear interaction is apparent only when there is significant overlap of the circulating waves, it only appears at close range, giving a plausible explanation for the short-range nature of the strong nuclear force.

• The *weak nuclear force* is not a force between particles like the strong nuclear force and the long-range forces, but instead involves a self-interaction within the internal structure of some of the more complicated circulating waves (*e.g.*, those representing the nucleons). In the wave theory of matter, the stable modes of standing waves (solitons) are the fundamental particles. But some of these modes are apparently unstable and subject to splitting up into pieces, each of which is a stable mode of standing wave. One inherent feature of this process is that the parent wave mode undergoes a change of topology - its amount of spin per rotation changes. It is this topological change which makes the process "slower" and "weaker" than direct particle-to-particle (wave mode-to-wave mode) interactions characterized by the strong nuclear force.

The concept of a "weak nuclear force" is required in the current state of understanding only because the Newtonian concept of force still influences our understanding of nuclear interactions. The concept of the strong nuclear force as an attractive force between nucleons is inadequate to explain why individual nucleons such as neutrons are unstable. But in the wave model of matter, both the strong nuclear force and the weak nuclear "force" have a common interpretation in terms of the localized wave mode (soliton) that is a nucleon. The strong nuclear force is a nonlinear wave interaction between nucleons and the weak nuclear force is an instability in the wave pattern of a single nucleon. A separate "weak nuclear force" (in the Newtonian sense) is not required.

Gone from the wave model description of particle interactions is any notion of force or force field acting between particles. It is replaced with simple wave interference between the (nonlinear) circulating waves and the (linear) waves of the ripple field. This wave interference follows simply and necessarily from the fundamental wave nature of matter.

Also gone is the need to introduce interaction particles to account for the observed interactions. Particle-particle interactions are described simply and naturally in terms of wave interference.

# 7 Conclusion - prospects for a unified theory of fundamental physics

To summarize the understanding of the fundamental forces of nature according to the wave model of matter it is useful to keep in mind that the circulating waves ("particles") are intrinsically nonlinear and the background displacement wave fields that they generate behave in a linear fashion. Within this context we have the following relationships:

$$\text{field/field} \Longrightarrow \text{linear superposition - no interaction}$$
$$\text{field/particle} \Longrightarrow \text{gravity, electromagnetism}$$
$$\text{particle/particle} \Longrightarrow \text{strong nuclear force}$$
$$\text{particle self-interaction instability} \Longrightarrow \text{weak nuclear force}$$

The important point is that a single phenomenon – wave interference – offers the possibility of accounting for *all* of the fundamental forces of nature in a way that follows naturally and necessarily from the circulating wave model of matter. In fact, the model *requires* the existence of these wave-wave interactions that we identify as the fundamental forces of nature. It is impossible to imagine a theory based on the circulating wave model of matter that does not include these modes of interaction. With the point-particle model of matter, the forces between particles have to be added in an *ad hoc* manner simply because they are observed in nature but with no understanding of what causes these forces. With the circulating wave model of matter, not only do the "mysteries" of the quantum wave phenomena of matter receive a natural explanation, but the classical forces of interaction between particles also receive a natural explanation in terms of wave-wave interactions. The space wave theory of matter opens up a new pathway that may finally make it possible to develop a true "theory of everything."

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