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# Teaching Quantum Physics Without Paradoxes

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**A**lthough the resolution to the wave-particle paradox has been known for 80 years,<sup>1,2</sup> it is seldom presented. Briefly, the resolution is that material particles and photons are the quanta of extended spatially continuous but energetically quantized fields. But because the resolution resides in quantum field theory and is not usually spelled out in ordinary language, it is neither generally understood nor generally taught, especially not in the context of nonrelativistic quantum physics. The purpose of this paper is to provide that resolution and to suggest that we teach introductory quantum physics from this viewpoint.

Most introductions to quantum physics, whether in a general introductory physics course or a modern physics course, devote considerable time to presenting the apparently contradictory wave and particle natures of material particles and photons. Students, and perhaps instructors, are left feeling confused about how they are supposed to view electrons, photons, etc. Are they waves? Particles? Sometimes one and sometimes the other? Usually, a true paradox (self-contradiction) is presented: Electrons are pictured as particles traveling one by one through a double-slit apparatus, yet they impact in a statistically formed interference pattern on the screen, indicating that each electron “knows” that both slits are open. In some sense, then, each electron went through both slits—a typical field behavior—even though they are imagined to be tiny particles. This is confusing, to say the least, and it is unnecessary.

I want to emphasize that I’m not proposing any

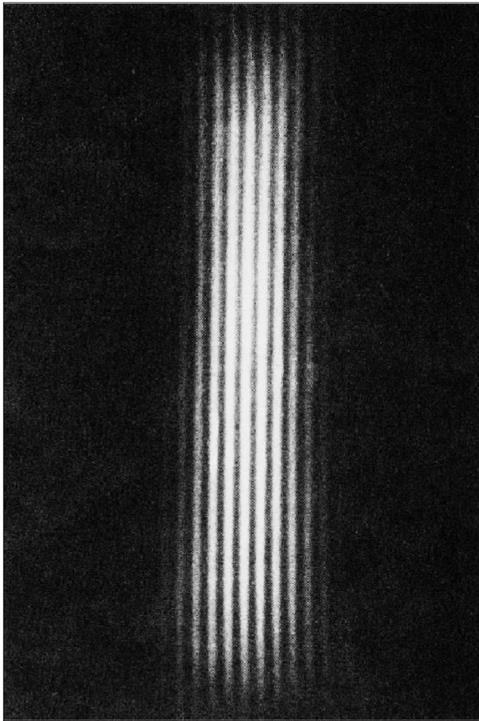
alteration of the traditional mathematical formalism (Schroedinger equation, operators, etc.) of introductory quantum physics, and I certainly do not propose teaching quantum field theory to introductory students. I propose only that we incorporate the idea of photons and material particles as field quanta into introductory pedagogy.

This paper is a follow-up on a previous paper presenting the quantum field approach as a better way to teach introductory quantum physics.<sup>3</sup> This paper discusses the consequences of this approach for the wave-particle paradox.

## The Paradox

Figures 1 and 2 point out the essence of the paradox. Young’s experiment (Fig. 1) shows that a monochromatic (i.e. mono-energetic) light beam interferes on the viewing screen when it shines through two narrow parallel slits, indicating that light is a wave in a field. But Young’s experiment done in dim light using time-lapse photography shows that the interference pattern builds up from particle-like impacts on the screen, indicating that light is made of particles (Fig. 2).

The same paradox occurs with material beams such as electron beams. When Young’s experiment is performed using a mono-energetic electron beam instead of a mono-energetic light beam, the beam forms an interference pattern on the screen (Fig. 3)! Yet the same experiment done using a “dim” electron beam in time-lapse “photography” shows that the interference pattern builds up from particle-like impacts on the screen (Fig. 4).

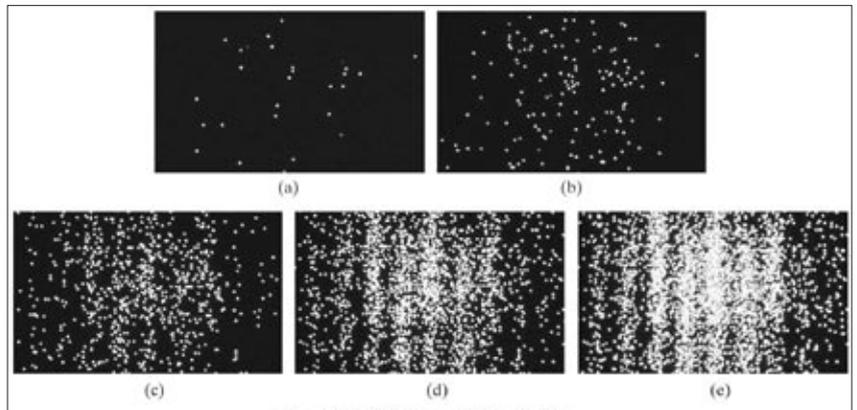


**Fig. 1. Outcome of Young's double-slit experiment with a light beam. (Copyright, Pearson Prentice-Hall)**

## The Resolution

As a prerequisite to understanding the resolution of the paradox, it must be understood that fundamental fields such as the electromagnetic (EM) field are physically real, and not simply mathematical fictions. Energy considerations convinced Maxwell that EM fields are real: When an EM signal is transmitted from A to B, energy is lost by A and *later* gained by B. Where was the energy in the meantime? In the field! Ergo, fields are real.<sup>7</sup>

For the case of radiation, the resolution of the wave-particle paradox follows from a single new quantum principle: The EM field is quantized. More precisely, when oscillating at frequency  $f$ , the energy of the field is restricted to the values  $0, hf, 2hf, 3hf$ , etc. (plus the "vacuum energy"  $hf/2$ ). Because of this restriction, when the field interacts with a localized object such as an atom in the viewing screen, it must give up an entire "quantum" of energy  $hf$  to that atom. This quantum comes from the entire continuous, space-filling field—a "nonlocal" effect—and it interacts instantaneously and randomly with the screen in accordance with the probability amplitude specified by the EM

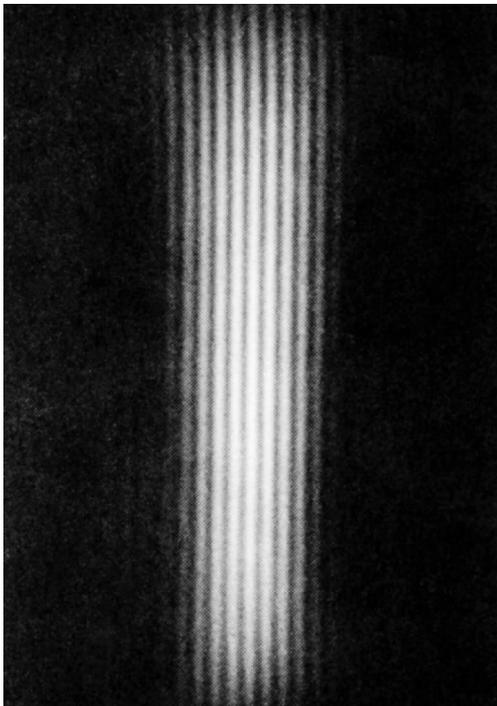


**Fig. 2. Young's experiment in dim light using time-lapse photography showing that the interference pattern builds up from particle-like impacts on the screen.<sup>4</sup> (Copyright, Pearson Prentice-Hall)**

field. We see immediately that nonlocality and uncertainty are inherent in quantum physics.

Thus, a photon is not really a particle. It is simply a way of talking about the energy increments  $hf$  of a spread-out, continuous EM field. These increments carry energy, which implies (because of special relativity) that they carry momentum. Because this energy and momentum is transferred to any atom with which the field interacts, photons hit like particles even though they are not particles. Thus, the paradox is resolved.

The resolution for electrons and other material particles is similar but with one additional detail. Experimental results such as Fig. 3 show that there is a new type of field in nature called the "electron-positron field" or, more generally, a "matter field." Like the EM field, this field is quantized. More specifically, for a mono-energetic electron beam, the energy of the matter field is restricted to the values  $0, mc^2, 2mc^2, 3mc^2$ , etc., where  $mc^2$  is the total energy of the electron (i.e.,  $m$  is the inertial mass). The rest of the discussion goes through precisely as it did for photons, except that the field equations are no longer Maxwell's equations but, instead, Schrodinger's equation (assuming the energies are nonrelativistic). Thus, electrons and other microscopic particles are not Newtonian particles at all. They are simply energy increments of a field, like photons. Again, the paradox is resolved: Electrons are quanta of a continuous matter field. They travel like fields but because they carry energy and momentum and "collapse" nonlocally to the point of interaction, they hit like particles.

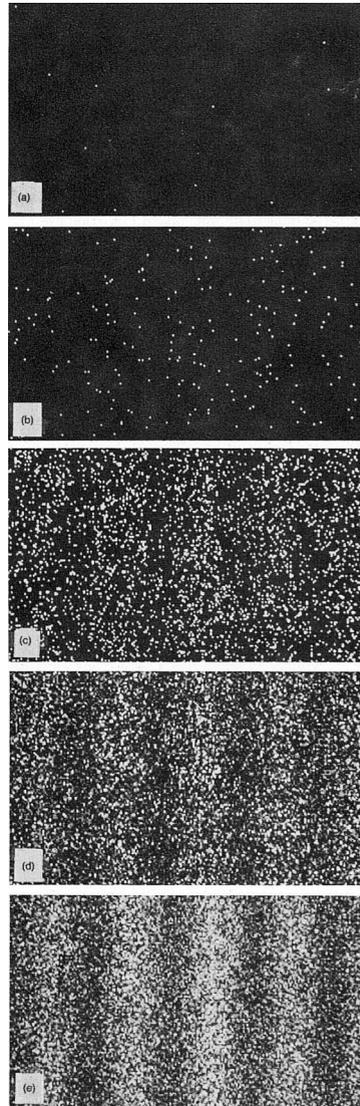


**Fig. 3. The double-slit experiment using an electron beam instead of a light beam.<sup>5</sup> (Copyright, Pearson Prentice-Hall)**

As Robert Mills (of the Yang-Mills theory of fundamental interactions) says, “The only way to have a consistent relativistic theory is to treat *all* the particles of nature as the quanta of fields.... Electrons and positrons are to be understood as the quanta of excitation of the electron-positron field, whose ‘classical’ field equation, the analog of Maxwell’s equations for the EM field, turns out to be the Dirac equation, which started life as a relativistic version of the single-particle Schroedinger equation.”<sup>8</sup>

### Further Comments

Along with the general theory of relativity, quantum field theory is widely recognized as our best and most fundamental theory of the way the universe works. The theory is founded on the notion that the universe is made of quantum fields. As Steven Weinberg puts it, “Material particles can be understood as the quanta of various fields, in just the same way as the photon is the quantum of the electromagnetic field.”<sup>9</sup> And, “In its mature form, the idea of quantum field theory is that quantum fields are the basic ingredients of the universe, and the particles are just bundles of energy and momentum of the fields.”<sup>10</sup>



**Fig. 4. The double-slit experiment using a low-intensity electron beam in time-lapse photography. As in Fig. 2, the interference pattern builds up from particle-like impacts on the screen.<sup>6</sup> (Copyright, Pearson Prentice-Hall)**

Indeed, it’s been pointed out since at least 1988<sup>11</sup> that such effects as the Lamb shift, where the hydrogen atom’s energy is affected by vacuum fluctuations, and the Cassimir effect, where the quantum vacuum field exerts an inward pressure on two uncharged parallel plates, show that quantum fields have measurable effects even when they contain no particles (no photons). We conclude that a field ontology, rather than a particle ontology, is the consistent way to view fundamental physics.

Although the quantized field approach resolves the wave-particle paradox, it does not remove wave-particle duality. EM radiation and matter have both wave and particle characteristics. For example, they come through both slits, but they hit the screen like particles.

When the Schrodinger equation is introduced in introductory courses, it should be emphasized that this is not merely the equation for a mathematical probability amplitude, but is actually the field equation for a physically real matter field analogous to Maxwell's equations for the physically real radiation field.

The quantized field approach to elementary quantum physics is put into practice in the author's conceptual physics textbook for nonscience students.<sup>12</sup>

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