

Electrons as field quanta: A better way to teach quantum physics in introductory general physics courses

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I. Introduction

I propose a conceptual change in the way we teach non-relativistic quantum mechanics in introductory courses, including non-mathematical courses for non-scientists, math-based physics survey courses for scientists, and general modern physics courses. Traditional instruction treats radiation as a quantized electromagnetic wave and hence observable only as discrete field quanta, while treating matter as particles that are accompanied by a wave function. In other words, traditional instruction views radiation as fundamentally a field phenomenon, and matter as fundamentally a particle phenomenon. But quantum field theory has a more unified view, according to which both radiation and matter are continuous fields with both photons and material particles quanta of these fields. As Weinberg has put 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.”¹ 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.”^{2,3} The quantum field theory view of radiation and matter clarifies particle identity issues, dispels students’ Newtonian misconceptions about matter, arguably resolves the wave-particle paradox, is the accepted view of contemporary physics,^{2,3} and might be the simplest and most effective teaching approach for all students. I propose that we make this field-theory viewpoint the conceptual basis for teaching non-relativistic quantum mechanics.

So that there not be misunderstandings, I do not propose any change of the present mathematical formalism for teaching non-relativistic quantum mechanics, and do not propose

teaching quantum field theory to introductory students. I propose only that we incorporate the qualitative notion of material particles as field quanta into introductory pedagogy.

This paper is organized around four experiments that highlight the fundamental symmetry between radiation and matter: The double-slit experiment for both radiation and matter, showing that both are waves in a field; and a time-resolved or “time-lapse” look at both experiments, showing that the interference fringes are formed by particle-like field quanta.

II. Electrons as field quanta

Consider the experimental results shown in Figs. 1 through 4. These experiments highlight not only the dual wave-particle nature of radiation and matter that is central to quantum physics, but also the symmetry between radiation and matter that is central to quantum field theory.

Young’s experiment (Fig. 1) is evidence for the wave nature of light, confirming that light is a wave in a field – an extended entity that comes through both slits and interferes with itself. Figure 2 is evidence that this wave is quantized, that is, it appears as localized bundles or quanta having energy $h\nu$. Because these field quanta are localized and carry energy and momentum, they qualify as particles, although of a very non-Newtonian sort because they are really excitations of a continuous field, and it is the *entire field* that is excited rather than some particular point within the field. A closer look shows that the field-screen interactions occur randomly on the screen (see Fig. 2), but their statistical distribution is described by the intensity of the interference pattern (see Fig. 1). Thus a predetermined wave pattern, quantum indeterminacy, particles (photons), and the probabilistic interpretation are all implicit in Figs. 1 and 2. Other experiments such as the photoelectric effect can highlight the same essentials, but the double-slit results are pedagogically more direct and compelling, and have direct analogues in experiments with matter (see Figs. 3 and 4). In any case, evidence for light quanta has been used for decades to introduce students to quantum physics.

Figures 3 and 4 are the obvious analogues for matter of Figs. 1 and 2 for radiation. Here we enter new pedagogical territory. Traditional instruction is inconsistent with the analogy between the two pairs of figures. According to traditional instruction, matter is fundamentally made of particles, particles that as far as students can know, are Newtonian and thus have persistent identities and follow definite paths. The quantum aspect of these particles is that they

are accompanied by a spatially-extended wave that comes through both slits and somehow directs the particles to strike the screen in an interference pattern.

A cursory inspection of Figs. 1-4 and quantum field theory both suggest that traditional instruction has it backward. Just as Fig. 1 is evidence that light is a wave in a physical field, Fig. 3 is evidence that matter is a wave in a field – an extended real physical entity that comes through both slits and interferes with itself. That is, when we say that “an electron came through the double-slit,” we really mean that an extended singly-excited field came through the double-slit. This field cannot be an electromagnetic field because a similar pattern appears with all beams of matter, even uncharged neutron beams, atomic beams, and C_{60} (buckeyball) molecular beams.⁴ Thus, Fig. 3 is evidence for a new fundamental wave in nature, different from an electromagnetic wave. Figure 4 shows that, like electromagnetic waves, this wave is quantized, that is, it interacts as bundles or “quanta.” Depending on the nature of the beam, these bundles are called electrons, neutrons, atoms, or C_{60} molecules, for example.

That’s where particles come from! Photons, quarks, electrons, and atoms are all quanta of various continuous space-filling fields. More precisely, they are quantized excitations of the vibrations of fields. Although excitations belong to the entire field, they must interact locally; they have energy and momentum so they qualify as particles, but of a very non-Newtonian sort. Because they are excitations of the entire field, they have no individual identity and can be created and destroyed. The basic physical entity is the underlying field.

What should this new physical field be called? In addition to the electromagnetic field, the standard model posits an electron field, various quark fields, and eleven other fundamental fields.⁵ Composite material particles such as protons and C_{60} molecules are the quanta of composite proton and C_{60} fields. We need a single name for all those fields whose quanta are material particles. “Matter field” is conventional, but misleading because “matter waves” can be confused with classical sound waves in matter. “Wave function” or “psi” is incorrect, because the non-relativistic quantum mechanics wave function for N particles is a probabilistic wave in $3N$ dimensions, while a quantum field is a real physical field in 3 dimensions. The term “fermion field” has been suggested.⁶ I will use the dual term “fermion/matter field,” leaving readers free to choose which of the two terms they prefer. This terminology denotes any of the various material quantum fields, for example, electron field and proton field.

The quantum field theory interpretation resolves the wave-particle paradox while retaining both the wave and particle character of quantum physics.⁷ As noted by Dirac, "...one can treat a field of radiation as a dynamical system, whose interaction with an ordinary atomic system may be described by a Hamiltonian ... the Hamiltonian for the interaction of the field with an atom is of the same form as that for the interaction of an assembly of light-quanta with the atom. There is thus a complete formal reconciliation between the wave and the light-quantum points of view."⁸ "Instead of working with a picture of the photons as particles, one can use instead the components of the electromagnetic field. One thus gets a complete harmonizing of the wave and corpuscular theories of light."⁹ Hence "Dirac's work closes the circle and non-relativistic quantum mechanics finds its final form. The riddle of the particle-wave nature of radiation, which had so strongly motivated theoretical physics since 1900, is solved."¹⁰

For the double-slit experiment with electrons, the conceptual resolution is that an excited fermion/matter field comes through both slits; although the excitation belongs to the entire field, the field is quantized (it must have enough energy for either 0, 1, or 2 electrons,...), so it must interact with the screen only in discrete quanta (that is, whole electrons). Resolving this paradox does not banish the mysteries of non-relativistic quantum mechanics, namely non-locality and indeterminacy. These two basic features are unaltered by the resolution of the wave-particle paradox. Moreover, although quantum field theory resolves the apparent paradox, it does not remove wave-particle duality. Quantum fields have both wave properties due to their field nature, and particle properties due to the quantization of the fields.

III. Teaching suggestions

Fields pervade all of modern physics. Students must understand this concept before grappling with quantum physics. Fields are probably best taught in connection with classical electromagnetism. We should stress the electromagnetic field concept, apart from quantitative details such as $E = F/q$ and $E = kq/R^2$. An electromagnetic field is the effect that a charged particle has on the surrounding space: not on the things in space, but the space itself. It is a disturbance of space, a stress in space. As Weinberg has put it, "fields are conditions of space itself, considered apart from any matter that may be in it."¹¹

An electromagnetic field surrounds every charged object, and exists wherever another charged object, if placed there, would feel an electromagnetic force exerted by the first charged

object. The emphasis is on “would.” An electromagnetic field is the *possibility* of an electromagnetic force – it exists wherever an electromagnetic force *would* be exerted *if* there were something there to feel it – which there might or might not be.

Convincing students that electromagnetic fields are physically real and not merely a convenient fiction is easy once they understand electromagnetic radiation. We can describe a thought experiment along the following lines: Suppose you hold up a charged transparency and briefly shake it once. Velma stands on the moon (it is a thought experiment) holding another charged transparency, initially at rest. The single quick shake of your transparency sends out a brief electromagnetic wave pulse that reaches the moon about one second later, causing a brief shake of Velma’s transparency. Energy was clearly required to shake Velma’s transparency. This energy must have come from your transparency a second earlier. Where was that energy during the intervening second, when neither transparency was shaking? It was in the empty (that is, essentially devoid of matter) space between the Earth and the moon. It was in the field! So fields contain energy. And energy is certainly physically real. Ergo, electromagnetic fields are physically real, despite the fact that they are not made of matter and can exist in otherwise empty space where there are no material particles.¹²

Instruction in quantum physics should begin with the fundamentals of radiation and matter, and not with complex phenomena such as the hydrogen spectrum. We could follow Bethe’s advice and begin with the photoelectric effect.¹³ But, as mentioned, Figs. 1 and 2 are simpler and more direct. In any case, it is wise to remain close to specific experiments while teaching a topic as elusive as quantum physics.

Figure 1 is understandable in terms of electromagnetic waves, but Fig. 2 requires a new concept: *quantized* electromagnetic waves. Quantization means that the vibrations of the entire field are restricted to a discrete set of energies, so that any interactions must involve the entire field losing (or gaining) a quantum of energy. When an interaction with the screen occurs, the entire field loses one quantum of energy and deposits it at the interaction point. Thus, interactions with the screen occur only in small particle-like bundles or quanta (because each one carries a definite quantity) of energy. These bundles, called photons, appear randomly, but with probabilities that are determined by a predictable wave pattern.

These ideas require no mathematics, but they are not easy and demand careful teaching, preferably using inquiry techniques. One misunderstanding to watch for is the notion that the

classical electromagnetic field theory of light is now replaced by a new theory in which light is a stream of particles. This misunderstanding simply replaces one classical theory with another. The modern view is that light is a wave in a continuous field, but this field is quantized. This view implies that light has both a wave (electromagnetic field) and a particle (photon) aspect. I can think of no more direct illustration of this view than Figs. 1 and 2.

Another important misconception is that the wave pattern is caused by Newtonian-like forces between different photons and thus arises only when large numbers of photons are simultaneously present in the region between the slits and the screen. A close look at Fig. 2 should correct this misconception, especially when students realize that the beam could be so dim that only one photon can appear on the screen.

Now we are ready to apply these ideas to matter. There are no new concepts here – only the familiar concepts of field and field quantization. Just as the understanding of the quantum nature of light can begin with Young's experiment, the quantum understanding of matter can begin with the double-slit experiment for electrons. We see in Fig. 3 that, like the light beam, an electron beam is a wave that comes through both slits and interferes with itself. But, as discussed, this wave cannot be an electromagnetic wave. We call the new wave a “fermion/matter wave”—a wave in a new kind of field called a “fermion/matter field.”

Everything that was said about quantized electromagnetic waves applies to fermion/matter waves. Figure 4 shows that the fermion/matter wave is quantized with quanta that are called electrons, neutrons, atoms, for example, depending on the source of the wave. These particles appear indeterminately on the screen, but with probabilities that are determined by the wave (more precisely, the probability density is proportional to the squared modulus of the fermion/matter field). The discussion of wave-particle duality and possible misconceptions applies here exactly as it did for electromagnetic waves.

Besides being simpler, this approach provides significant insights that are missing in traditional instruction. For example, because electrons are simply quantized excitations of an entire space-filling field, they are all identical and can be created and destroyed when they interact with other particles. We see why they are so strongly non-Newtonian: Being only field excitations, they “belong” to the entire field and have no independent or permanent existence. And we see the deep similarity between matter and radiation: Particles of both kinds are merely quantized excitations of fields.

Only after a full discussion of the foregoing conceptual fundamentals are students ready for quantitative details such as the Schrodinger equation, and such complex topics as the quantum atom. We should begin the quantum atom with a conceptual introduction to the full quantum view of the hydrogen atom, using diagrams of its possible quantum states.¹⁴ Such diagrams picture the discrete set of possible vibrations of the fermion/matter wave in the atom. More mechanistic (but more mathematically tractable) models, such as the Bohr model of hydrogen, should be introduced only after teaching the correct quantum concepts. Because it is compounded of Newtonian and quantum notions, Bohr's brilliantly-conceived model must be presented carefully in order not to evoke or reinforce student misconceptions.

IV. Conclusion

Because I am retired, I have been unable to test these ideas in the classroom. I hope that somebody will study the pedagogy of the field theory approach to quantum physics using the comparative methods of physics education research. I would be delighted to hear the experiences of instructors and physics education researchers who try this teaching approach.

V. Conceptual Questions

These questions could be assigned as homework or used as in-class peer instruction questions.¹⁵

1. A small electrically charged particle is placed in the middle of an isolated and otherwise empty box. Consider a point x inside and near a particular corner of the box. At x , there is (a) an electromagnetic force, (b) an electromagnetic field, (c) matter, (d) electric charge, (e) energy. (Answers: b and e).
2. In the double-slit experiment using an electron beam, the pattern seen on the screen is (a) a single point of light at the center of the screen, caused by electrons striking this point on the screen; (b) two points of light, one directly behind slit A formed by electrons passing through slit A, and the other directly behind slit B formed by electrons passing through slit B; (c) two spread-out regions where the electrons strike the screen, directly behind both slits, due to a fermion/matter field passing through both slits; (d) an interference pattern due to a fermion/matter field passing through both slits; or (e) an

interference pattern caused by the forces that electrons exert on each other in the region between the slits and the screen. (Answer: d).

3. During the double-slit experiment using a light beam, the region between the slits and the screen contains (a) a fermion/matter field, (b) a stream of electrons moving toward the screen, (c) an electromagnetic field, (d) a stream of photons moving toward the screen, or (e) none of the above. (Answer: c).

4. During the double-slit experiment using a beam of uncharged particles such as neutrons, the region between the slits and the screen contains (a) a fermion/matter field, (b) a stream of neutrons moving toward the screen, (c) an electromagnetic field, (d) a stream of photons moving toward the screen, or (e) none of the above. (Answer: a).

5. In the double-slit experiment with electrons, it is possible to predict (a) the individual impact point of each electron on the screen, (b) the overall pattern of hits on the screen, as formed by a large number of electrons, (c) the slit that each electron goes through, (d) all of the above, or (e) none of the above. (Answer: b)

6. In what ways are electrons and photons similar? (a) Both contain electric charge, (b) both are field quanta, (c) both are particles, (d) both are fields, (e) all of the above. (Answers: b and c)

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Figure 1. Outcome of Young's double-slit experiment with a light beam. The photograph shows the interference pattern as it appears on a viewing screen placed a short distance behind the slits.

Figure 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.¹⁶

Figure 3. The double-slit experiment using an electron beam instead of a light beam. As in Young's experiment, the photograph shows the interference pattern as it appears on a viewing screen placed a short distance behind the slits.¹⁷

Figure 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.¹⁸

References and notes

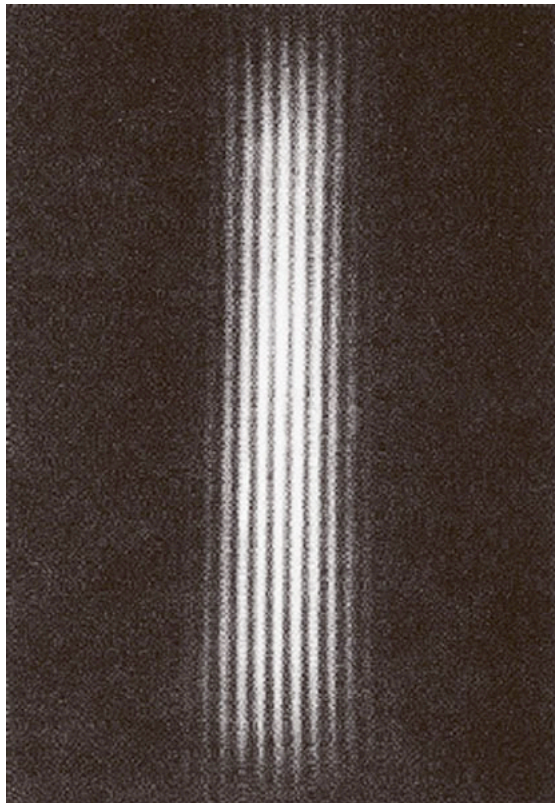


Figure 1. Outcome of Young's double-slit experiment with a light beam. The photograph shows the interference pattern as it appears on a viewing screen placed a short distance behind the slits.

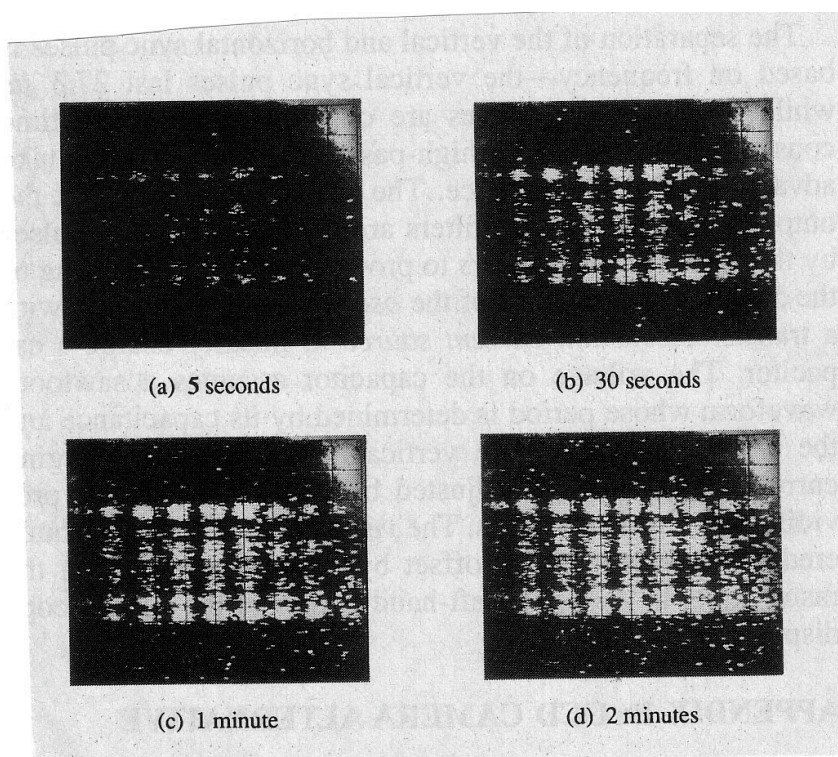


Figure 2. Young's experiment in dim light, using "time lapse" photography, showing that the interference pattern builds up from particle-like impacts on the screen.¹⁹

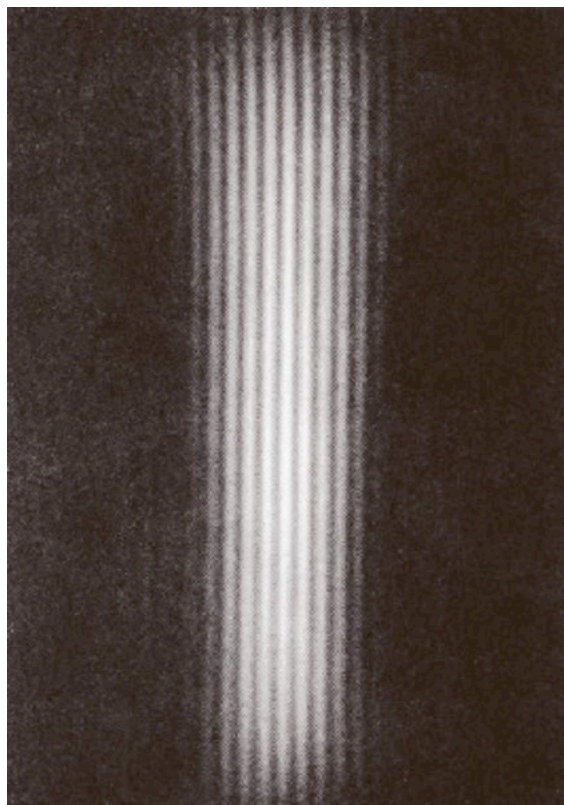


Figure 3. The double-slit experiment using an electron beam instead of a light beam. As in Young's experiment, the photograph shows the interference pattern as it appears on a viewing screen placed a short distance behind the slits.²⁰

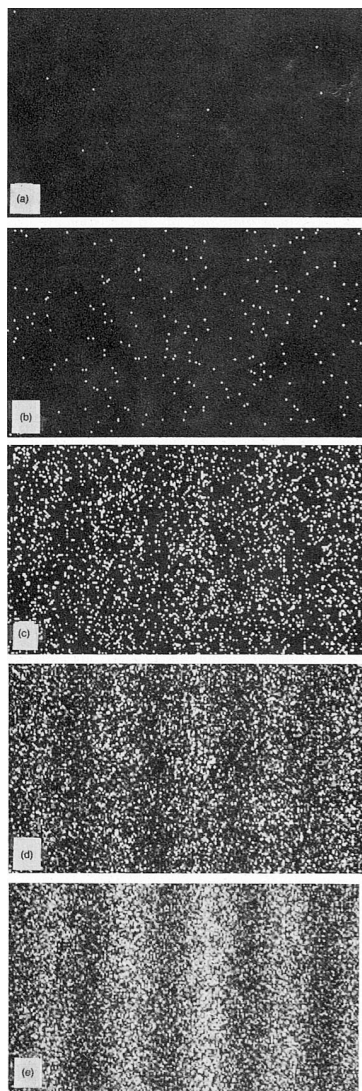


Figure 4. The double-slit experiment using a low-intensity electron beam, in time-lapse photography. As in Figure 2, the interference pattern builds up from particle-like impacts on the screen.²¹

¹Steven Weinberg, quoted in Heinz Pagels, *The Cosmic Code* (Bantam Books, New York, 1983), p. 239

²Steven Weinberg, in *Conceptual Foundations of Quantum Field Theory*, edited by Tian Yu Cao (Cambridge University Press, Cambridge, 1999), p. 242.

³For a more explicit, but still non-mathematical, statement of the quantum field theory view of both photons and electrons, see Robert Mills, *Space Time and Quanta* (W. H. Freeman, New York, 1994), Secs. 16.2 and 16.4.

⁴Olaf Nairz, Markus Arndt, and Anton Zeilinger, “Quantum interference experiments with large molecules,” *Am. J. Phys.* **71**, 319-325 (2003).

⁵Steven Weinberg, *Facing Up: Science and Its Cultural Adversaries* (Harvard University Press, Cambridge, MA, 2001), pp. 73-74

⁶Tian Yu Cao, private communication.

⁷ As T. Y. Cao has stated, "...once we see electrons as field quanta, the wave-particle duality is resolved" (private communication). Also see Michael Redhead, "A philosopher looks at quantum field theory," in *Philosophical Foundations of QFT*, edited by Harvey R. Brown and Rom Harre (Oxford University Press, Oxford, 1988), pp. 9-23, and T. Y. Cao, *Conceptual Developments of 20th Century Field Theories* (Cambridge University Press, Cambridge, 1997), pp. 170-173.

⁸ P. A. M. Dirac, "The quantum theory of the emission and absorption of radiation," *Proc. Roy. Soc. (London)* **A114**, 243-265 (1927).

⁹ P. A. M. Dirac, "The origin of quantum field theory," in *The Birth of Particle Physics*, edited by L. M. Brown and L. Hoddeson (Cambridge University Press, Cambridge, 1983), p. 49.

¹⁰ R. Jost, "Foundation of quantum field theory," in *Aspects of Quantum Theory*, edited by P. A. M. Dirac, Abdus Salam, and Eugene Paul Wigner (Cambridge University Press, Cambridge, 1972), p. 69.

¹¹ Ref. 5, p. 167. Similarly, Einstein insisted that fields are real. In Albert Einstein and Leopold Infeld, *The Evolution of Physics* (Simon and Schuster, New York, 1938), pp. 148-156, we find, "The electromagnetic field is, in Maxwell's theory, something real. The electric field is produced by a changing magnetic field, quite independently, whether or not there is a wire to test its existence."

¹² This argument persuaded Maxwell that electromagnetic fields were physically real. See Howard Stein in *Historical and Philosophical Perspectives of Science*, edited by Roger H. Stuewer (Gordon and Breach, New York, 1989), p. 299. A similar argument applies to any force that is transmitted non-instantaneously.

¹³ Hans A. Bethe, "My experience in teaching physics," *Am. J. Phys.* **61**, 972-973 (1993).

¹⁴ Art Hobson, *Physics: Concepts and Connections* (Prentice Hall, Upper Saddle River, NJ, 2003), 3rd ed.

¹⁵ Eric Mazur, *Peer Instruction: A User's Manual* (Prentice Hall, Upper Saddle River, NJ, 1997); David E. Meltzer and Kandiah Manivannan, "Promoting interactivity in physics lecture classes," *Phys. Teach.* **34**, 72-76 (1996); D. W. Bullock et al., "Enhancing the student-instructor interaction frequency," *Phys. Teach.* **40**, 535-541 (2002).

¹⁶ Wolfgang Rueckner and Paul Titcomb, "A lecture demonstration of single photon interference," *Am. J. Phys.* **64**, 184-188 (1996).

¹⁷ Claus Jonsson, "Electron diffraction at multiple slits," *Am. J. Phys.* **42**, 4-11 (1974).

¹⁸ A. Tonomura, J. Endo, T. Matsuda, T. Kawasaki, and H. Exawa, "Demonstration of single-electron buildup of an interference pattern," *Am. J. Phys.* **57**, 117 (1989). The experiment, including the photographic results, is reviewed in George Greenstein and Arthur G. Zajonc, *The Quantum Challenge* (Jones and Bartlett Publishers, Sudbury, MA, 1997), pp. 1-7.

¹⁹ Wolfgang Rueckner and Paul Titcomb, "A lecture demonstration of single photon interference," *Amer. J. Phys.* **64**, 184-188 (1996).

²⁰ Claus Jonsson, "Electron diffraction at multiple slits," *Am. J. Phys.* **42**, 4-11 (1974).

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