RESPONSE TO "THE SCANDAL OF QUANTUM MECHANICS," BY N. G. VAN KAMPEN [AM. J. PHYS. 76, 989–990 (2008)]

Kudos to N. G. van Kampen for his authoritative commentary on quantum physics.[1] It is indeed a scandal that there are still so many "interpretations" of quantum physics when the theory actually provides a complete and adequate description of phenomena. Van Kampen correctly attributes these unnecessary interpretations to the difficulties experienced by "someone who still thinks of electrons as individual particles rather than as manifestations of a wave function." Indeed, electrons are not individual particles.

I would add only one point to van Kampen's remarks. It's a point only about van Kampen's (and most others') choice of words, but I think it can make a big difference in the pedagogy of this difficult, nonintuitive, subject.[2] "Manifestations of a wave function" leaves the reader to question what is meant by the "wave function." It would be clearer, and more consistent with quantum field theory which is our most accurate form of quantum physics, to speak instead of "manifestations of a matter field." More precisely, electrons (and quarks, protons, atoms, etc.) are field quanta—irreducible bundles of a quantized matter field—just as photons are irreducible bundles of a quantized radiation field. When referring to electrons, field theorists call this field the "electron-positron field." The relativistic field equations such as the Dirac equation for this field and for other matter fields reduce, in the nonrelativistic limit, to the Schrödinger equation. That is, the Ψ of the Schrödinger equation is the nonrelativistic approximation to the quantized matter fields of relativistic quantum field theory.

The universe is made of quantized fields. As Steven Weinberg puts it, "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."[3] Thus the nonintuitive aspects of quantum physics, in particular quantum uncertainty and quantum entanglement, result from the circumstance that the fundamental constituents of the universe are fields, not particles. These fields are, however, quantized, which implies that they exhibit many particle-like aspects.

[1] N. G. van Kampen, "The scandal of quantum mechanics," Am. J. Phys. **76**, 989–990 (2008).

[2] Art Hobson, "Teaching quantum physics without paradoxes," Phys. Teach. **45**, 96–99 (2007); "Electrons as field quanta," Am. J. Phys. **73**, 630–634 (2005). This approach to teaching quantum physics is incorporated into a conceptual physics textbook for nonscientists: Art Hobson, *Physics: Concepts & Connections*, 4th ed. (Pearson, Upper Saddle River, NJ, 2007).

[3] Steven Weinberg, in *Conceptual Foundations of Quantum Field Theory*, edited by Tian Yu Cao (Cambridge U. P., Cambridge, 1999), p. 242.

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