32 The Atom and the Quantum

The Part Seven opening photo is of William Davis, son of close friends marine-biologist Alan and Fe Davis.

Chapter opener photos are of four quantum physicists, all high achievers and a credit to their teaching institutions, David Kagan at California State University at Chico, Roger King at City College of San Francisco, Dean Zollman at Kansas State University, and Art Hobson at the University of Arkansas.

The profile for this chapter is Niels Bohr.

This is a history-oriented chapter, a continuation of Chapters 30 and 31. It is background for Chapters 33 and 34, but is not prerequisite to them. This chapter can, with some discussion of atomic spectra, stand on its own as a continuation of Chapter 11, *The Atomic Nature of Matter*. For a short course, Chapter 11 followed by most of this chapter should work quite well. You may wish to lecture about the physicists who took part in the development of quantum mechanics. Ken Ford's new book, *The Quantum World—Quantum Physics for Everyone*, is a flavorful resource. You can build from the Thompson plum-pudding model of the atom, to Rutherford's gold foil experiments, and to the Bohr model. Apply de Broglie waves to the electrons that surround the atomic nucleus, and tie this to the relative sizes of the atoms.

Quantum mechanics has more cracks than most theories of physics—some hairline and some wide. Take notice of charlatans and others who promote junk science in the guise of science, who seek footholds in these cracks, and who attempt to ride on the hard-earned reputation of quantum theory.

Suggested complementary reading:

Ford, K. W. *The Quantum World: Quantum Physics for Everyone*. Cambridge, MA: Harvard University Press, 2004. A fascinating account of the development of quantum physics with emphasis on the participating physicists.

Ford, K. W. *101 Quantum Questions: What You Need to Know About the World You Can't See*. MA: Harvard University Press, 2011.

I was lucky to illustrate these two books by Ken Ford, both down-to-earth reading. And to enjoy his passion of soaring (in addition to his love of quantum physics) consider Ken's:
In Love With Flying, Philadelphia: H Bar Press, 2007.

Gamow, George. *Thirty Years That Shook Physics*. New York: Dover, 1985. A historical tracing of quantum theory by someone who was part of it.

Hey, A. J., and P. Walters. *The Quantum Universe.* New York: Cambridge University Press, 1987. A broad view of modern physics with many illustrations.

Pagels, H. R. *The Cosmic Code: Quantum Physics as the Language of Nature*. New York: Simon & Schuster, 1982. An oldie but goody book for the general reader.

Gleick, James. *Genius: The Life and Science of Richard Feynman*. New York: Vintage, 1993. An inspiring book about an intriguing person.

I include this chapter as supplementary reading for students who are interested in this major area of physics that is more removed from their everyday environment. I do not lecture on this material and have no suggested lecture for this chapter.

Discussion of the figures in the chapter is instructive. Do any of your students even know about the CRT TV tube shown in Figure 32.4? Millikan's oil drop experiment, Figure 32.5, is fascinating. And the Ritz combination principle of Figure 32.9 is a topic I found intriguing back when I was first introduced to it. That the numbers tell the story is quite interesting! Also interesting is how the orbiting wave forms of Figure 32.10 nicely lead to the graphics of Figure 32.11. And how the models of the atom progressed, as simplified in Figure 32.13.

Quantum physics is concerned with the extremely small. Today's physicists, after all, are involved in exploring extremes: the outer limits of the fast and the slow, hot and cold, few and many, and big and small. In a light sense it can be said that everything in the middle is engineering.

The chapter discusses the character of quantum mechanics. There is some confusion in the minds of many people about the wave-particle duality. Much of this confusion is failing to see that light behaves as a wave when it travels in empty space, and lands like a particle when it hits something. It is mistaken to insist it must be both a particle and a wave at the same time. This is not the case, despite some writers who try to make this mysteriously profound. What something *is* and *what it does* are not the same. Another misconception fostered in popular and not-so-popular literature is that quantum theory is nondeterministic and that it is acausal. Solutions to the fundamental quantum equation are unique, continuous, and incorporate the principle of causality. Another misconception is that quantum theory reveals nature as a game of probability. Although some predictions about certain quantities are sometimes probabilistic, it doesn't follow that the predictions of quantum mechanics are necessarily uncertain. Quantum mechanics, in fact, leads to extremely accurate results (it predicts for example, the energy of the hydrogen atom in its ground state to one part in 10^{12}). Whether quantum mechanics gives definite or probabilistic answers to questions depends on the nature of the questions. For questions inappropriate to the quantum level, quantum mechanics gives probabilistic answers. For appropriate questions, its answers are definite. See more on this in the Reference Frame essay, *Ask a Foolish Question...by* Herman Feshback and Victor Weisskopf in the October 1988 issue of *Physics Today*.

In graduate school I was disappointed in myself for not being able to visualize quantum mechanics. I felt personally deficient. At the time, I would have benefited from this Feynman quote: "I think it is safe to say that no one understands quantum mechanics. Do not keep saying to yourself, if you can possibly avoid it, 'but how can it get like that?' because you will go 'down the drain' into a blind alley from which nobody has yet escaped. Nobody knows how it can be like that."

Something that I would also have benefited from back then was the visual materials available today. A great example is the Physlets® that are featured in *Physlet Quantum Physics*, by Anne J. Cox, Mario Belloni, and Wolfgang Christian, published by Prentice Hall but now freely available at www.compadre.org/physlets.

Another source that provides visualization of quantum physics is the work of Dean Zollman and his creative friends at Kansas State University. See http://web.phys.ksu.edu/vqm/. Dean has enhanced visualizing quantum mechanics.

The chapter treats the matter-wave concept that gives a clearer picture of the electrons that "circle" the atomic nucleus. Instead of picturing them as tiny BBs whirling like planets, the matter-wave concept suggests we see them as smeared standing waves of energy—existing where the waves reinforce, and nonexisting where the waves cancel (Figures 32.11 and 32.12). This is also highlighted in my screencast *Matter Waves*.

The philosophical implications of quantum mechanics is left to your lecture. At minimum you might warn your class that there are many people who have much to say about quantum physics who don't understand it. Quantum physics does not come in the neat package that Newtonian physics comes in, and is not all sewed up like other less complex bodies of knowledge. It is an ill-understood theory. Because it works so well it is a widely respected theory. We must watch for anything weird being attributed to quantum mechanics, and be wary of pseudoscientists who attempt to fit their own theories into the cracks of quantum mechanics, and ride on the back of its hard-earned reputation.

A few words about Planck's constant. If its numerical value were just a bit higher or lower, stars wouldn't shine. Likewise for the gravitational constant G, where a slight change would mean stars wouldn't exist—nor would we. Aha, does this mean that the precise value of these and other fundamental physical constants are coincidentally "just right" for a universe, for life … and, especially, us? A lot of people wonder about this "fine-tuning" of the constants. Some hypothesize that the constants preceded the advent of the universe, and some offer supernatural explanations.

But I don't see that fine-tuning needs an explanation. After all, do we need an explanation as to why $\pi = 3.14159$? The way I see it, constants are measurements of a nature that exists, not the reason for that existence. Given what we know now, we can only say that nature determines the constants, the constants don't determine nature.

Now as to why the universe exists at all, no scientific explanation is convincing. Nobody knows. But that's a much bigger story.

New to this edition is a box on the Higgs Boson, page 612.

Practicing Physics Book:
- Light Quanta

Next-Time Questions:
- Zinc Ball on Electroscope

Hewitt-Drew-It! Screencast: •*Matter Waves*

Answers and Solutions for Chapter 32

Reading Check Questions

1. Most particles remain undeflected because of the empty space within atoms.
2. Rutherford discovered the atomic nucleus, that it was tiny, positive, and massive.
3. Franklin postulated that electricity is an electric fluid that flows from place to place.
4. A cathode ray is a beam of electrons.
5. Deflection of the ray indicated the presence of electric charge.
6. J.J. Thomson discovered the existence of electrons.
7. Robert Millikan found the mass and charge of the electron.
8. Balmer discovered regularity in atomic spectra.
9. Rydberg and Ritz discovered that the frequency of a spectral line in the spectrum of an element equals the sum or difference of two other spectral lines.
10. Bohr postulated light emission was the result of an electron transition between electron orbits in an atom.
11. Yes, if there is at least one intermediate energy state that the electron can transition to along the way.
12. The relationship is given by $\Delta E \sim f$.
13. The circumferences of orbits are discrete because they are made up of particular whole-number wavelengths of the electron.
14. In the first orbit, one wavelength makes up the circumference. In the second, two wavelengths. In the n^{th} orbit, n wavelengths.
15. Electrons don't spiral because they are composed of waves that reinforce themselves.
16. The wave function represents the possibilities that can occur for a quantum system.
17. The probability density function is the square of the wave function.
18. An electron's distance from the nucleus, most of the time, exists at a location described by Bohr's first orbit.
19. What corresponds is the overlap between new and old theories, if new theory is valid.
20. Schrodinger's equation would apply to the solar system, but not be useful.

Think and Explain

21. Photons from the ultraviolet lamp have greater frequency, energy, and momentum. Only wavelength is greater for photons emitted by the TV transmitter.

22. Blue, which has a higher frequency, and therefore greater photon energy.

23. A small fraction of the alpha particles were deflected (scattered) through a large angle, indicating such a strong electric field within the atom that the positive charge must be concentrated in a small central core—a core that is massive as well as small because the rebounding alpha particles showed no appreciable loss of KE.

24. The dense concentration of positive charge and mass in the atomic nucleus accounts for the backscattering of alpha particles as they ricochet off the gold atoms of the thin foil. This backscattering would not occur if the positive charge and mass of the atom were spread throughout the volume of the atom, just as a golf ball would not bounce backward when striking a piece of cake, or even when colliding with a tennis ball or another golf ball. A golf ball will bounce backward if it strikes a massive object such as a bowling ball, and in a similar way, some of the alpha particles bounce backward when encountering the massive atomic nucleus, and also the enormously strong electric field in its vicinity.

25. Rutherford's experiments showed that the positive charge must be concentrated in a small core, the atomic nucleus.

26. Spectral lines are as characteristic of the elements as fingerprints are of people. Both aid identification.

27. The same amount of energy is needed to return the electron, as it gave to the photon when dropping to the ground state.

28. If the energy spacings of the levels were equal, there would be only two spectral lines. Note that a transition between the 3rd and 2nd level would have the same difference in energy as a transition

between the 2nd and first level. So both transitions would produce the same frequency of light and produce one line. The other line would be due to the transition from the 3rd to the first level.

29. The smallest orbit would be one with a circumference equal to one wavelength, according to the de Broglie model.

30. The particle nature of the electron best explains the photoelectric effect, while the wave nature best explains the discreteness of energy levels.

31. If we think of electrons as orbiting the nucleus in standing waves, then the circumference of these wave patterns must be a whole number of wavelengths. In this way the circumferences, and also the radii of orbits are discrete. Since energy depends upon this radial distance, the energy values are also discrete. (In a more refined wave model, there are standing waves in the radial as well as the orbital direction.)

32. Helium's electrons are in one filled shell. The filled shell means that bonding with other elements is rare. Lithium has two shells, the first filled and the second with only one of eight electrons in it, making it very reactive with other elements. The shell concept was too brief in Chapter 11 for this question to be asked then.

33. The frequency of every photon is related to its energy by $E = hf$, so if two frequencies add up to equal a third frequency, two energies add up to equal a third energy. In a leapfrog transition such as from the third to the first energy level in Figure 32.10, energy conservation requires that the emitted energy be the same as the sum of the emitted energies for the cascade of two transitions. Therefore the frequency for the leapfrog transition will be the sum of the frequencies for the two transitions in the cascade.

34. Yes. In atoms, electrons move in waves with speeds on the order of 2 million m/s.

35. Constructive interference to form a standing wave requires an integral number of wavelengths around one circumference. Any number of de Broglie wavelengths not equal to a whole number would lead to destructive interference, preventing the formation of a standing wave.

36. Both use Bohr's concept of energy levels in an atom. An orbital is represented by the easier-to-visualize orbit.

37. The answer to both questions is yes. Since a particle has wave properties and a wavelength related to its momentum, it can exhibit the same properties as other waves, including diffraction and interference.

38. The amplitude of a matter wave is called its wave function, represented by the symbol ψ. Where ψ is large, the particle (or other material) is more likely to be found. Where ψ is small, the particle is less likely to be found. (The actual probability is proportional to ψ^2.)

39. Atoms would be larger if Planck's constant were larger. We can see this from de Broglie's equation (wavelength = h/momentum), where if h were larger for a given momentum, the wavelengths of the standing waves that comprise electron shells would be larger, and hence atoms would be larger.

40. What waves is the probability amplitude.

41. Both are consistent. The correspondence principle requires agreement of quantum and classical results when the "graininess" of the quantum world is not important, but permits disagreement when the graininess is dominant.

42. They overlap for a collection of atoms large enough for classical physics to have some validity but small enough for quantum effects still to be present. For smaller atomic groupings, quantum mechanic dominates. For larger groupings, Newton's laws dominate.

43. Bohr's correspondence principle says that quantum mechanics must overlap and agree with classical mechanics in the domain where classical mechanics has been shown to be valid.

44. Narrowly defined, the correspondence principle applies only to the transition from quantum to classical behavior, which takes place in the atomic and molecular domain. But we can define the principle more broadly, stating that a theory for one domain or set of circumstances, and another theory for another domain and another set of circumstances (like a theory for small things and a theory for big things, or a theory for slow things and a theory for fast things, or one for cold things and another for hot things) should correspond to each other in the region where the domains overlap. This broadened definition of the correspondence principle is relevant for all good theory in all fields of knowledge.

45. It is the wave nature of matter that keeps atoms apart and gives bulk to matter in the world around us. Otherwise everything would collapse and there would be no matter as we know it.

46. The speed of light is large compared with the ordinary speeds with which we deal in everyday life. Planck's constant is small in that it gives wavelengths of ordinary matter far too small to detect and energies of individual photons too small to detect singly with our eyes.

47. Open-ended.

Think and Discuss

48. It would emit a continuous spectrum. Its energy would change gradually and continuously as it spiraled inward and it would radiate at its rotational frequency, which would be continuously increasing.

49. Electrons can be boosted to many energy levels, and therefore make many combinations of transitions to ground level and levels in between. The vast variety of transitions produce the vast numbers of spectral lines in a spectroscope. Even hydrogen, with a single electron, has many lines, most of which are in the ultraviolet and infrared.

50. The laws of probability applied to one or a few atoms give poor predictability, but for hordes of atoms, the situation is entirely different. Although it is impossible to predict which electron will absorb a photon in the photoelectric effect, it is possible to predict accurately the current produced by a beam of light on photosensitive material. We can't say where a given photon will hit a screen in double-slit diffraction, but we can predict with great accuracy the relative intensities of a wave-interference pattern for a bright beam of light. Predicting the kinetic energy of a particular atom as it bumbles about in an atomic lattice is highly inaccurate, but predicting the average kinetic energy of hordes of atoms in the same atomic lattice, which measures the temperature of the substance, is possible with high precision. The indeterminacy at the quantum level can be discounted when large aggregates of atoms so well lend themselves to extremely accurate macroscopic prediction.

51. Electrons have a definite mass and a definite charge, and can sometimes be detected at specific points—so we say they have particle properties; electrons also produce diffraction and interference effects, so we say they have wave properties. There is a contradiction only if we insist the electron may have only particle OR only wave properties. Investigators find that electrons display both particle and wave properties.

52. Classical physics predicts that accelerating charged particles should emit radiation. If this happened, the loss of energy should be accompanied by a spiraling of the electron into the atomic nucleus (akin to the fate of satellites that encounter the atmosphere in low Earth orbit.

53. Einstein thought quantum mechanics is not fundamental, but has underpinnings yet to be discovered.

54. The philosopher was speaking of classical physics, the physics of the macroscopic world, where to a high degree of accuracy the same physical conditions do produce the same results. Feynman was speaking of the quantum domain where for small numbers of particles and events, the same conditions are not expected to produce the same results.