31 Light Quanta

Photo openers are of Phil Wolf, CERN physicists, Anne Cox, and Gary Williams. Both Phil and Anne are physics department chairpersons at their respective colleges.

Max Planck is featured in the opening profile. In his honor is the Planck spacecraft that scans the sky for the infinitesimal but informative clues to the earliest moments of the universe.

Louis de Broglie's doctoral thesis about the wave nature of matter was so radical that his professors were uncertain about accepting it. After asking Einstein about it and gaining his approval, the thesis was accepted. Five years later de Broglie's thesis won the Nobel Prize in physics.

This chapter is part of a three-chapter sequence—Chapters 30 - 32, which serves as a transition to the quantum nature of the atom in Part 7.

Unless you wish to lecture about the physicists who led us to our present understanding of light, and how the processes and developments leading to these findings were discovered and fashioned into the building blocks of quantum mechanics, the chapter can be assigned as reading and not treated during lecture time. If lecture time is used to support the chapter, demonstrate the photoelectric effect as described below. Perhaps the concept most interesting in the chapter to expand upon in lecture is the uncertainty principle.

Practicing Physics Book:
- Light Quanta

Next-Time Questions:
- Lamp Glow

Hewitt-Drew-It! Screencasts: •*The Quantum World* •*Planck's Constant and Photons* •*Photoelectric Effect* •*Particle Diffraction* •*Quantum Uncertainty* •*The Uncertainty Principle*

SUGGESTED LECTURE PRESENTATION

Birth of the Quantum Theory

Begin by citing the flavor of physics at the turn of the century, that many in the physics community felt that the bulk of physics was in the can and only applications and engineering were left. And then along came Einstein and Max Planck, who fell through cracks that turned out to be Grand Canyons! Continue with a historical perspective.

Quantization and Planck's Constant

You may or may not wish to discuss Planck's work with blackbody radiation and how it led to the notion that energy occurs in discrete amounts called quanta (only slightly mentioned in the text).

Photoelectric Effect

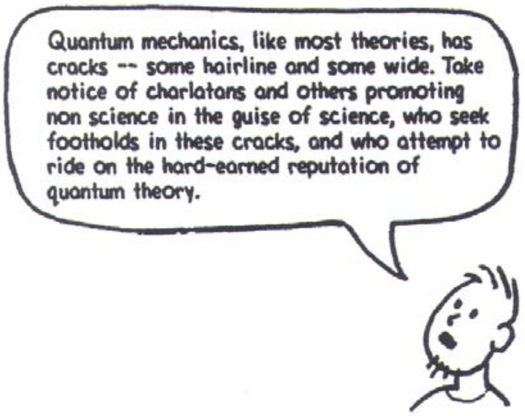
> DEMONSTRATION: Demonstrate the photoelectric effect by placing a freshly polished piece of zinc on an electroscope and illuminate it with an open carbon arc lamp (no glass lens). To focus the beam, use a quartz lens (to pass the UV). Show that a positively charged electroscope will not discharge when the light shines on the zinc plate. But that a negatively charged electroscope will quickly lose its charge, showing that the negative charges (electrons!) are ejected form the zinc surface by the light. Show the blockage of UV light by placing a piece of glass in the path of the light beam. This is evidenced by the stopping of the discharge process. If you have a quartz prism, pass the light through a slit, then through the prism, and onto the zinc. Show that the negatively charged electroscope discharges only when the portion of the spectrum beyond the violet end strikes the zinc plate.

Go a step further as Mikhael Grote and William Heinmiller do. Have students test the effectiveness of various sunscreens and lotions. Simply spread different creams or lotions on the zinc plate before charging the electroscope. (*The Physics Teacher*, Vol. 34, Number 9, Dec. 1996.)

Asking and Answering Questions: The answers one gets often depends on the way the question is asked. This is illustrated by the two monks who wished to smoke in the prayer room of a monastery. The first monk wrote a letter to his superior asking if it was permissible to smoke while praying. The answer was a resounding no. The second monk wrote a letter to his superior asking if it was permissible to pray while smoking. The answer was a resounding yes. In a sort of similar way, many of the perplexities of quantum physics have to do with the way questions are asked, and more particularly with what kind of questions are asked. For example, asking for the energy of a hydrogen atom in its first excited state has a definite answer, accurate to one part in 10^{12}. The answer to asking exactly when the electron makes its transition to the ground state, on the other hand, is probabilistic. The probabilistic answers to such questions fosters the false notion that there are no exact answers at the quantum realm. Questions appropriate to the quantum realm, however, are crisply and precisely answered by quantum mechanics.

Quantum Physics

Cite the behavior of light as being wavelike in traveling from place to place, but being particlelike when incident upon matter, as evident in various **double slit experiments**. It travels like waves and lands like particles. Discuss the **wave-particle duality**, and the photon-by-photon buildup of the photograph of Figure 31.5. Like others, de Broglie was in the right place at the right time, for the notion of particles having wave properties was at hand. De Broglie showed Planck's constant again with his formula that relates the wavelength of a "matter wave" with its momentum. So matter, like light, has wave properties. When incident upon a target its matter nature is evident. We don't ordinarily notice the wave nature of matter only because the wavelength is so extremely small. The footnote on page 608 in the chapter illustrates this. (Interestingly enough, de Broglie did little physics after his one large contribution. He died in 1987.) Discuss the **uncertainty principle** and what it means and what it does not mean. End with Bohr's principle of **complementarity**.



Answers and Solutions for Chapter 31

Reading Check Questions

1. All three supported the wave theory.
2. The photoelectric effect supports the particle theory.
3. Planck considered the electron vibrations, not light, as quantized.
4. A quantum of light is the photon.
5. Yes, f stands for frequency in general.
6. Lower energy is red light; radio waves.
7. Photons of violet have more energy and are therefore more successful at dislodging electrons.
8. Ejection depends on individual encounter, not average encounter, therefore a lot of red light does no ejection, whereas a single photon of violet will.
9. They are composed of tiny units.
10. Light acts as a particle when interacting with film.
11. Light travels in a wavelike way from one location to another.
12. Light acts as a particle when encountering a detector.
13. Light behaves as a wave in transit, as a particle when absorbed.
14. The photoelectric effect is evidence of the particle nature of light.
15. Traveling through slits, light acts in a wavelike way. Hitting the screen as particle-like. The pattern of hits is wavelike.
16. Of the three, only the electron has significant quantum uncertainties.
17. The product $\Delta p \Delta x$ is equal to or more than h bar.
18. The measurements show one or the other, not both.
19. As with momentum, only one of the other can be precise.
20. Passive observation does not affect what is looked at; active observation, where probing occurs, does affect what is looked at.
21. Wave and particle aspects of both matter and radiation are necessary, complementary parts of the whole.
22. The ancient yin-yang symbol showed opposites as components of a wholeness.

Think and Solve

23. Frequency is speed/wavelength: $f = (3 \times 10^8 \text{ m/s})/(2.5 \times 10^{-2} \text{ m}) = 1.2 \times 10^{10}$ Hz. Photon energy is Planck's constant × frequency: $E = hf = (6.63 \times 10^{-34} \text{ J s})(1.2 \times 10^{10} \text{ Hz}) = 8.0 \times 10^{-24}$ J.

24. De Broglie wavelength = Planck's constant/momentum, so we need the electron's momentum. It is $p = mv = (9.1 \times 10^{-31} \text{ kg})(3.0 \times 10^7 \text{ m/s}) = 2.7 \times 10^{-23}$ kg m/s. The de Broglie wavelength is then $\lambda = h/p = (6.6 \times 10^{-34})/(2.7 \times 10^{-23}) = 2.4 \times 10^{-11}$ m, less than the diameter of a single atom.

25. The ball's momentum is $mv = (0.1 \text{ kg})\ (0.001 \text{ m/s}) = 1.0 \times 10^{-4}$ kg m/s, so its de Broglie wavelength is $h/p = (6.6 \times 10^{-34} \text{ J s})/(1.0 \times 10^{-4} \text{ kg m/s}) = 6.6 \times 10^{-30}$ m, incredibly small relative even to the tiny wavelength of the electron. There is no hope of rolling a ball slowly enough to make its wavelength appreciable.

Think and Explain

26. Saying that something is quantized is saying it is composed of elementary units. Electric charge, for example, is composed of multiples of the charge of the electron, so we say charge is quantized. A gram of pure gold is quantized in that it is made of a whole number of gold atoms. In this chapter we learn that light—radiant energy—is also quantized.

27. Classical physics is primarily the physics known before 1900 that includes the study of motion in accord with Newton's laws and the study of electromagnetism in accord with the laws of Maxwell. Classical mechanics, often called Newtonian mechanics, is characterized by absolute predictability. After 1900 scientists discovered that Newtonian rules simply don't apply in the domain of the very small—the submicroscopic. This is the domain of quantum physics, where things are "grainy" and where values of energy and momentum (as well as mass and charge) occur in lumps, or quanta. In this domain, particles and waves merge and the basic rules are rules of probability, not certainty. Quantum physics is different and not easy to visualize like classical physics. We nevertheless tend to impress our classical wave and particle models on our findings in an effort to visualize this subatomic world.

28. $E \sim f$ is a proportion. When E is divided by f we have the constant h. With h the proportion becomes the exact equation $E = hf$. So we see h is the proportionality constant for the energy and frequency of a photon of light.

29. In accord with $E = hf$, the energy of a photon with twice the frequency has twice the energy. Violet photons are about twice as energetic as red photons.

30. Higher-frequency ultraviolet light has more energy per photon.

31. It makes no sense to talk of photons of white light, for white light is a mixture of various frequencies and therefore a mixture of many photons. One photon of white light has no physical meaning.

32. Higher-frequency green beam has more energy per photon.

33. Since red light carries less energy per photon, and both beams have the same total energy, there must be more photons in the beam of red light.

34. The kinetic energy of ejected electrons depends on the frequency of the illuminating light. With sufficiently high frequency, the number of electrons ejected in the photoelectric effect is determined by the number of photons incident upon the metal. So whether or not ejection occurs depends on frequency, and how many electrons are ejected depends on the brightness of the sufficiently high-frequency light.

35. It is not the total energy in the light beam that causes electrons to be ejected, but the energy per photon. Hence a few blue photons can dislodge a few electrons, where hordes of low-energy red photons cannot dislodge any. The photons act singly, not in concert.

36. Ultraviolet photons are more energetic.

37. Protons are held within nuclei deep within atoms. To eject a proton from an atom takes about a million times more energy than to eject an electron. So one would need a high-energy gamma-ray photon rather than a photon of visible light to produce a “photoprotonic” effect.

38. The photoelectric effect mainly depends on the particle nature of light. Whether or not an electron is knocked free depends on the photon’s frequency. So the wave model is part of the picture.

39. Some automatic doors utilize a beam of light that continuously shines on a photodetector. When you block the beam by walking through it, the generation of current in the photodetector ceases. This change of current then activates the opening of the door.

40. *Electric eye*: A beam of light is directed to a photosensitive surface that completes the path of an electric circuit. When the beam is interrupted, the circuit is broken. The entire photoelectric circuit may be used as a switch for another circuit. *Light meter*: The variation of photoelectric current with variations in light intensity activates a galvanometer, or its equivalent, that is calibrated to show light intensity. *Sound track*: An optical sound track on motion picture film is a strip of emulsion of variable density that transmits light of variable intensity onto a photosensitive surface, which in turn produces an electric current of the desired variations. This current is amplified and then activates the loudspeaker.

41. The photoelectric effect is discharging the ball. Some of the excess electrons are being “knocked off” the ball by the ultraviolet light. This discharges the ball. If the ball is positively charged, however, it already has a deficiency of electrons, and knocking off more tends to increase the charge rather than decrease it. (Fewer electrons are dislodged by ultraviolet light from the positive ball than from the negative ball. Can you see why?)

42. Young’s explanation of the double-slit experiment is based on the wave model of light; Einstein’s explanation of the photoelectric effect uses a model in which light is composed of particles. The effectiveness of one model or another doesn’t invalidate the other model, particularly in this instance where the models are used to describe completely different phenomena. Models are not to be judged as being “true” or “false” but as being useful or not useful. The particle model of light is useful in making sense of the details of the photoelectric effect, whereas the wave model of light is not useful in understanding these details. On the other hand, the wave model of light is useful for understanding the details of interference, whereas the particle model is not. The effectiveness of one model over another means simply that: One model is more effective than another. As we gather more data and gain new insights, we refine our models. The fact that two quite different models are needed to describe light lead to what is called the “wave-particle duality,” a central part of quantum physics.

43. An explanation is the following: Light refracting through the lens system is understandable via the wave model of light, and its arrival spot by spot to form the image is understandable via the particle model of light. How can this be? We have had to conclude that even single photons have wave properties. These are waves of probability that determine where a photon is likely or not likely to go. These waves interfere constructively and destructively at different locations on the film, so the points of photon impact are in accord with probability determined by the waves.

44. Diffraction, polarization, and interference are evidence of the wave nature of light; the photoelectric effect is evidence of the particle nature of light.

45. A photon behaves like a wave when in transit, and like a particle when it is emitted or absorbed.

46. No. Complementarity isn't a compromise, but suggests that what you see depends on your point of view. What you see when you look at a box, for example, depends on whether you see it from one side, the top, and so on. All measurements of energy and matter show quanta in some experiments and waves in others. For light, we see particle behavior in emission and absorption, and wave behavior in propagation between emission and absorption.

47. The electron microscope.

48. By absorbing energy from the impact of a particle or photon.

49. The photon loses energy, so its frequency decreases. (Actually we say one photon is absorbed and another, lower-energy, photon is emitted.)

50. Uranium possesses more momentum. Hydrogen has the longer wavelength, which is inversely-proportional to momentum.

51. The cannonball obviously has more momentum than the BB traveling at the same speed, so in accord with de Broglie's formula the BB has the longer wavelength. (Both wavelengths are too small to measure.)

52. The principal advantage of an electron microscope over an optical microscope is its ability to see things that are too small for viewing with an optical microscope. This is because an object cannot be discerned if it is smaller than the wavelength of the illuminating beam. An electron beam has a wavelength that is typically a thousand times shorter than the wavelength of visible light, which means it can discern particles a thousand times smaller than those barely seen with an optical microscope.

53. Protons of the same speed as electrons would have more momentum, and therefore smaller wavelengths, and therefore less diffraction. Diffraction is an asset for long-wavelength radio waves, helping them to get around obstructions, but it is a drawback in microscopes, where it makes images fuzzy. Why are there not proton microscopes? There are. We call them atomic accelerators. The high momenta of high-velocity protons make it possible to extract detailed information on nuclear structure, illuminating a domain vastly smaller than the size of a single atom.

54. Planck's constant would be zero.

55. If somebody looks at an electron on the tip of your nose with an electron beam or a light beam, then its motion as well as that of surrounding electrons will be altered. We take the view here that passively looking at light after it has reflected from an object does not alter the electrons in the object. We distinguish between passive observation and probing. The uncertainty principle applies to probing, not to passive observation. (This view, however, is not held by some physicists who assert any measure, passive or probing, alters that being measured at the quantum level. These physicists argue that passive observation provides knowledge, and that without this knowledge, the electron might be doing something else or might be doing a mixture, a superposition, of other things.)

56. The uncertainty principle refers only to the quantum realm, and not the macroworld.

57. Heisenberg's uncertainty principle applies *only* to quantum phenomena. However, it serves as a popular metaphor for the macro domain. Just as the way we measure affects what's being measured, the way we phrase a question often influences the answer we get. So to various extents we alter that which we wish to measure in a public opinion survey. Although there are countless examples of altering circumstances by measuring them, the uncertainty principle has meaning only in the sub-microscopic world.

58. No, for there is an important distinction between properties that are measurable and properties that are predictable, whether classical or quantum mechanical. As an example of a classical system for which exact prediction is not possible, consider a pinball machine. You could take a slow-motion movie of a ball that makes its way down through the forest of metal pins to finally reach a position at the bottom. You could analyze this movie to understand everything that happened. By hindsight (20/20 vision!) you could see how the ball responded to interaction with each pin. But this hindsight does not mean you can predict the final position of the next ball you drop through the maze of pins because the ball is sensitive to the tiniest differences in its initial speed and each interaction with a pin. This is classical uncertainty. In the quantum world, uncertainty is of a more fundamental kind, but the idea is the same. Knowing by measurement exactly how an electron moved does not enable you to predict just how it will move in the future.

59. The uncertainty principle refers only to the quantum realm, and not the macroworld. Air escaping from a tire is a macro-world event.

60. The question is absurd, with the implication that eradicating butterflies will prevent tornadoes. If a butterfly can, in principle, cause a tornado, so can a billion other things. Eradicating butterflies will leave the other 999,999,999 causes untouched. Besides, a butterfly is as likely to *prevent* a tornado as to cause one.

61. Unless the term is meant to leap into a completely different realm, no, for a quantum leap is the *smallest* transition something can undergo.

62. This is perhaps the extreme in altering that which is being measured by the process of measuring itself, as well as an extreme case of academic misbehavior. The bristlecone pine, Old Methuselah, was the oldest known living thing in the world.

Think and Discuss

63. Finding materials that would respond photoelectrically to red light was difficult because photons of red light have less energy for image production than photons of green or blue light.

64. Conversion is from high-frequency high-energy stages to lower ones. If the reverse occurred, energy conservation would be violated.

65. The energy of red light is too low per photon to trigger the chemical reaction in the photographic crystals. Very bright light simply means more photons that are unable to trigger a reaction. Blue light, on the other hand, has sufficient energy per photon to trigger a reaction. Very dim blue light triggers fewer reactions only because there are fewer photons involved. It is safer to have bright red light than dim blue light.

66. When a photon of ultraviolet light encounters a living cell, it transfers to the cell an amount of energy that can be damaging to the cell. When a photon of visible light encounters a living cell, the amount of energy it transfers to the cell is less, and less likely to be damaging. Hence skin exposure to ultraviolet radiation can be damaging to the skin while exposure to visible light generally is not.

67. There will be colors toward the red end of the spectrum where the meter will show no reading, since no electrons are ejected. As the color is changed toward the blue and violet, a point will be reached where the meter starts to give a reading. If a color for which the meter reads zero is made more intense, the meter will continue to read zero. If a color for which the meter shows a reading is made more intense, the current recorded by the meter will increase as more electrons are ejected.

68. We can never definitely say what something *is*, only how it behaves. Then we construct models to account for the behavior. The photoelectric effect doesn’t prove that light is corpuscular, but supports the corpuscular model of light. Particles best account for photoelectric behavior. Similarly, interference experiments support the wave model of light. Waves best account for interference behavior. We have models to help us conceptualize what something *is*; knowledge of the details of how something behaves helps us to refine the model. It is important that we keep in mind that our models for understanding nature are just that: models. If they work well enough, we tend to think that the model represents what *is*.

69. The more massive proton has more momentum, while the electron with its smaller momentum has the longer wavelength.

70. The twice-as-fast electron has twice the momentum. By de Broglie's formula, wavelength = *h*/momentum, twice the momentum means half the wavelength. The slower electron has the longer wavelength.

71. As velocity increases, momentum increases, so by de Broglie's formula, wavelength decreases.

72. The momenta of moving things in our everyday environment are huge relative to the momenta of submicroscopic particles even when the everyday things are very slow and the particles are very fast. This is because the masses of the everyday objects are so huge compared with the particle masses. The large momenta, in accord with de Broglie's formula, correspond to incredibly short wavelengths. See the footnote about this in the chapter.

73. Planck's constant would be much much larger than its present value.
74. In the best spirit of science, from our observations we develop a theory that gives meaning to those observations. However, it is often the case that belief in a theory precedes observations and influences our perception of those observations and the meaning we give them. We should be aware of this "human factor." Sometimes it is very beneficial and sometimes it is not.

75. We don't know if an electron *is* a particle or a wave; we know it *behaves* as a wave when it moves from one place to another and behaves as a particle when it is incident upon a detector. The unwarranted assumption is that an electron must *be* either a particle *or* a wave. It is common to hear some people say that something can only be either this or that, as if both were not possible (like those who say we must choose between biological evolution *or* the existence of a supreme being).