Why does the photoelectric effect suggest that light has particle type properties?

Selected problem:

How the energy is quantized and why does the photoelectric effect suggest that light has particle type properties?

Theoretical background

By the late 19th century, many physicists thought their discipline was well on the way to explaining most natural phenomena. They could calculate the motions of material objects using Newton’s laws of classical mechanics, and they could describe the properties of radiant energy using mathematical relationships known as Maxwell’s equations, developed in 1873 by James Clerk Maxwell, a Scottish physicist. The universe appeared to be a simple and orderly place, containing matter, which consisted of particles that had mass and whose location and motion could be accurately described, and electromagnetic radiation, which was viewed as having no mass and whose exact position in space could not be fixed. Thus matter and energy were considered distinct and unrelated phenomena. Soon, however, scientists began to look more closely at a few inconvenient phenomena that could not be explained by the theories available at the time.

Blackbody Radiation. First Phenomena.

One phenomenon that seemed to contradict the theories of classical physics was blackbody radiation, which is electromagnetic radiation whose wavelength and color that depends on the temperature of the object. The wavelength of energy emitted by an object depends on only its temperature, not its surface or composition. Hence an electric stove burner or the filament of a space heater glows dull red or orange when heated, whereas the much hotter tungsten wire in an incandescent light bulb gives off a yellowish light (Figure 1).
Figure 1: Blackbody Radiation. When heated, all objects emit electromagnetic radiation whose wavelength (and color) depends on the temperature of the object. A relatively low-temperature object, such as a horseshoe forged by a blacksmith, appears red, whereas a higher-temperature object, such as the surface of the sun, appears yellow or white. Images used from Wikipedia.
The intensity of radiation is a measure of the energy emitted per unit area. A plot of the intensity of blackbody radiation as a function of wavelength for an object at various temperatures is shown in Figure 2. One of the major assumptions of classical physics was that energy increased or decreased in a smooth, continuous manner.

For example, classical physics predicted that as wavelength decreased, the intensity of the radiation an object emits should increase in a smooth curve without limit at all temperatures, as shown by the broken line for 6000 K in Figure 2. Thus classical physics could not explain the sharp decrease in the intensity of radiation emitted at shorter wavelengths (primarily in the ultraviolet region of the spectrum), which was referred to as the “ultraviolet catastrophe.”

In 1900, however, the German physicist Max Planck (1858–1947) explained the ultraviolet catastrophe by proposing that the energy of electromagnetic waves is quantized rather than continuous. This means that for each temperature, there is a maximum intensity of radiation that is emitted in a blackbody object, corresponding to the peaks in Figure 2, so the intensity does not follow a smooth curve as the temperature increases, as predicted by classical physics. Thus energy could be gained or lost only in integral multiples of some smallest unit of energy, a quantum (the smallest possible unit of energy). Energy can be gained or lost only in integral multiples of a quantum.
Figure 2: Relationship between the Temperature of an Object and the Spectrum of Blackbody Radiation It Emits. At relatively low temperatures, most radiation is emitted at wavelengths longer than 700 nm, which is in the infrared portion of the spectrum. The dull red glow of the electric stove element in Figure 1 is due to the small amount of radiation emitted at wavelengths less than 700 nm, which the eye can detect. As the temperature of the object increases, the maximum intensity shifts to shorter wavelengths, successively resulting in orange, yellow, and finally white light. At high temperatures, all wavelengths of visible light are emitted with approximately equal intensities. The white light spectrum shown for an object at 6000 K closely approximates the spectrum of light emitted by the sun.

Although quantization may seem to be an unfamiliar concept, we encounter it frequently. For example, musical instruments like a piano or a trumpet can produce only certain musical notes, such as C or F sharp. Because these instruments cannot produce a continuous range of frequencies, their frequencies are quantized. Even electrical charge is quantized: an ion may have a charge of 1 or 2 but not 1.33 electron charges.

Max Planck (1858–1947) postulated that the energy of a particular quantum of radiant energy could be described by the equation:

\[ E = h \]

where the proportionality constant \( h \) is called Planck's constant, one of the most accurately known fundamental constants in science.

\[ h = 6.626 \times 10^{-34} \text{ J\cdot s (joule-seconds)} \]

As the frequency of electromagnetic radiation increases, the magnitude of the associated quantum of radiant energy increases. By assuming that energy can be emitted by an object only in integral multiples of \( h \), Planck devised an equation that fit the experimental data shown in Figure 2. We can understand Planck's explanation of the ultraviolet catastrophe qualitatively as follows:

At low temperatures, radiation with only relatively low frequencies is emitted, corresponding to low-energy quanta. As the temperature of an object increases, there is an increased probability of emitting radiation with higher frequencies, corresponding to higher-energy quanta.

At any temperature, however, it is simply more probable for an object to lose energy by emitting a large number of lower-energy quanta than a single very high-energy quantum that corresponds to ultraviolet radiation. The result is a maximum in the plot of intensity of emitted radiation versus wavelength, as shown in Figure 2, and a shift in the position of the maximum to lower wavelength (higher frequency) with increasing temperature.
The Photoelectric Effect. Second Phenomena.

Only five years after he proposed it, Planck’s quantization hypothesis was used to explain a second phenomenon that conflicted with the accepted laws of classical physics.

When certain metals are exposed to light, electrons are ejected from their surface (Figure 3). Classical physics predicted that the number of electrons emitted and their kinetic energy should depend on only the intensity of the light, not its frequency. In fact, however, each metal was found to have a characteristic threshold frequency of light; below that frequency, no electrons are emitted regardless of the light’s intensity. Above the threshold frequency, the number of electrons emitted was found to be proportional to the intensity of the light, and their kinetic energy was proportional to the frequency. This phenomenon was called the photoelectric effect (A phenomenon in which electrons are ejected from the surface of a metal that has been exposed to light).

Figure 3: The Photoelectric Effect (a) Irradiating a metal surface with photons of sufficiently high energy causes electrons to be ejected from the metal. (b) A photocell that uses the photoelectric effect, similar to those found in automatic door openers. When light strikes the metal cathode, electrons are emitted and attracted to the anode, resulting in a flow of electrical current. If the incoming light is interrupted by, for example, a passing person, the current drops to zero. (c) In contrast to predictions using classical physics, no electrons are emitted when photons of light with energy less than $E_0$, such as red light, strike the cathode. The energy of violet light is above the threshold frequency, so the number of emitted photons is proportional to the light’s intensity.
Albert Einstein (1879–1955; Nobel Prize in Physics, 1921) quickly realized that Planck’s hypothesis about the quantization of radiant energy could also explain the photoelectric effect. The key feature of Einstein’s hypothesis was the assumption that radiant energy arrives at the metal surface in particles that we now call photons (a quantum of radiant energy, each of which possesses a particular energy energy E given by Equation (kinetic energy of ejected electron) Einstein postulated that each metal has a particular electrostatic attraction for its electrons that must be overcome before an electron can be emitted from its surface

\[
E_0 = h \nu
\]

If photons of light with energy less than \( E_0 \) strike a metal surface, no single photon has enough energy to eject an electron, so no electrons are emitted regardless of the intensity of the light. If a photon with energy greater than \( E_0 \) strikes the metal, then part of its energy is used to overcome the forces that hold the electron to the metal surface, and the excess energy appears as the kinetic energy of the ejected electron:

\[
\text{kinetic energy of ejected electron} = E - E_0 = h \nu = h \nu
\]

When a metal is struck by light with energy above the threshold energy \( E_0 \), the number of emitted electrons is proportional to the intensity of the light beam, which corresponds to the number of photons per square centimeter, but the kinetic energy of the emitted electrons is proportional to the frequency of the light. Thus Einstein showed that the energy of the emitted electrons depended on the frequency of the light, contrary to the prediction of classical physics.

The remarkable aspects of the photoelectric effect when it was first observed were:

1. The electrons were emitted immediately - no time lag!
2. Increasing the intensity of the light increased the number of photoelectrons, but not their maximum kinetic energy!
3. Red light will not cause the ejection of electrons, no matter what the intensity!
4. A weak violet light will eject only a few electrons, but their maximum kinetic energies are greater than those for intense light of longer wavelengths![i]
Planck’s and Einstein’s postulate that energy is quantized is in many ways similar to Dalton’s description of atoms. Both theories are based on the existence of simple building blocks, atoms in one case and quanta of energy in the other. The work of Planck and Einstein thus suggested a connection between the quantized nature of energy and the properties of individual atoms.

At the time he proposed his radical hypothesis, Planck could not explain why energies should be quantized. Initially, his hypothesis explained only one set of experimental data—blackbody radiation. If quantization were observed for a large number of different phenomena, then quantization would become a law. In time, a theory might be developed to explain that law. As things turned out, Planck’s hypothesis was the seed from which modern physics grew.

Why does the photoelectric effect suggest that light has particle type properties?
The properties of blackbody radiation, the radiation emitted by hot objects, could not be explained with classical physics. Max Planck postulated that energy was quantized and could be emitted or absorbed only in integral multiples of a small unit of energy, known as a quantum. The energy of a quantum is proportional to the frequency of the radiation; the proportionality constant $h$ is a fundamental constant (Planck’s constant).

Albert Einstein used Planck’s concept of the quantization of energy to explain the photoelectric effect, the ejection of electrons from certain metals when exposed to light. Einstein postulated the existence of what today we call photons, particles of light with a particular energy, $E = h$.

Both energy and matter have fundamental building blocks: quanta and atoms, respectively.[ii] In 1905 Einstein came to a conclusion that the pure wave theory of light is an oversimplification, and that the energy of a beam of light comes in finite chunks rather than being spread smoothly throughout a region of space. Explanation of the photoelectric effect led Einstein to propose photons as the quanta of electromagnetic wave energy.

[i] http://hyperphysics.phy-astr.gsu.edu/hbase/mod1.html