On the Planck-Einstein Relation

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Abstract

The Planck-Einstein relation ($E=h\nu$), a formula integral to quantum mechanics, says that a quantum of energy (E), commonly thought of as a photon, is equal to the Planck constant (h) times a frequency of oscillation of an atomic oscillator (ν, the Greek letter nu). Yet frequency is not quantized—frequency of electromagnetic radiation is well known in Nature to be a continuum extending over at least 18 orders of magnitude from extremely low frequency (low-energy) radio signals to extremely high-frequency (high-energy) gamma rays. Therefore, electromagnetic energy (E), which simply equals a scaling constant times a continuum, must also be a continuum. We must conclude, therefore, that electromagnetic energy is not quantized at the microscopic level as widely assumed. Secondly, it makes no physical sense in Nature to add frequencies of electromagnetic radiation together in air or space—red light plus blue light does not equal ultraviolet light. Therefore, if $E=h\nu$, then it makes no physical sense to add together electromagnetic energies that are commonly thought of as photons. The purpose of this paper is to look at the history of $E=h\nu$ and to examine the implications of accepting $E=h\nu$ as a valid description of physical reality. Recognizing the role of $E=h\nu$ makes the fundamental physics studied by quantum mechanics both physically intuitive and deterministic.

Introduction

On Sunday, October 7, 1900, Heinrich Rubens and wife visited Max Planck and wife for afternoon tea (Hoffmann, 2001). During the social conversation, Rubens mentioned that his most recent experimental data measuring spectral radiance from a black body at the longest wavelengths yet available, fit a new law suggested by Lord Rayleigh (1900) better than the empirical distribution law proposed by Wien (1897), for which Planck had worked out a derivation. By dinner, Planck sent a postcard to Rubens with a slight modification to Wien's law, blending the two laws together in the extremes by adding a minus one after the exponential term in the denominator (Figure 1). Within two days, Rubens informed Planck that Planck's new law for the spectral radiance of electromagnetic radiation from a black body at thermal equilibrium fit all available data extremely well.

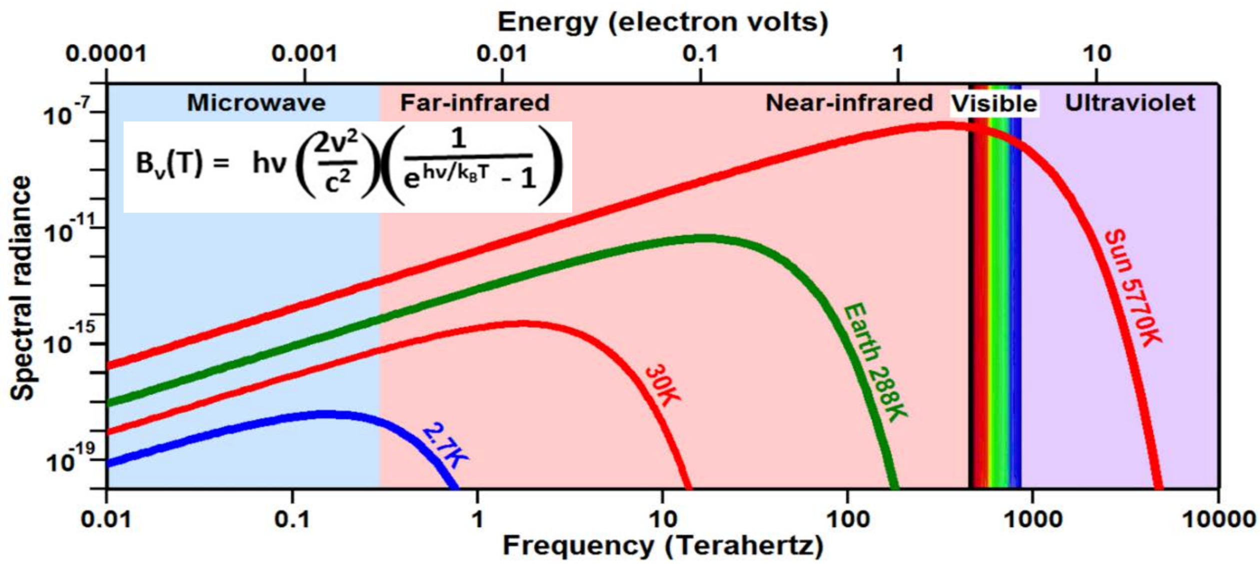

Figure 1. Planck's law shows that radiation from a warmer body has higher spectral radiance (spectral amplitudes of oscillation) at all frequencies than does radiation from a cooler body and exhibits its greatest amplitude at a higher frequency. Each solid line shows the spectral radiance radiated from a body at thermal equilibrium for the temperature shown. The equation for Planck's law is shown in the upper left where B_ν is the spectral radiance written in terms of Planck's constant (h), frequency (ν), velocity of light (c), the Boltzmann constant (k_b), and absolute temperature (T).

For Planck, however, this new equation was just "lucky intuition." As a theoretical physicist, he felt driven to derive the new equation from first principles based on Maxwell's wave theory of electromagnetic radiation. He explained the new equation

at the German Physical Society on October 19 and "after some weeks of the most strenuous work of my life" (Planck, 1920), presented a derivation at the Society on 14 December. Planck (1901) shows by reformulating Wien's displacement law, applying it to Planck's equation for entropy, and assuming that radiant energy consists of an integral number of "energy elements," "we then find that the energy element ε must be proportional to the frequency *ν*, thus: $\varepsilon = h\nu$."

Einstein (1905b) was the first scientist to take Planck's "energy elements" seriously, proposing what Einstein called a "light quantum" ($E=h\nu$) to explain the photoelectric effect and then arguing that light itself is quantized. Robert Millikan was convinced that Einstein's particle theory of light must be wrong because of overwhelming support for Maxwell's wave theory of light, but after nearly a decade of laboratory work, Millikan (1916) confirmed Einstein's predictions in every detail. Compton (1923) explained the Compton effect in terms of "radiation quanta" colliding with electrons, and de Broglie (1923) suggested that particles have a wavelike nature and, therefore, would have a wavelength. Lewis (1926) call this “light quantum” a photon as wave-particle duality for electromagnetic radiation (EMR) began to be widely accepted. E=h*ν* became known as the Planck-Einstein relation where E is widely accepted today as the energy of a photon. Most physicists today also think that the energies of photons can be added together to provide greater energy—i.e. energy at the microscopic level is currently thought of as both quantized and additive.

Planck (1901) considered E=h*ν* to be a mathematical trick or convenience and never appears to have thought deeply about its physical meaning. In 1931, he explained that introducing the energy quantum in 1900 was “a purely formal assumption and I really did not give it much thought except that no matter what the cost, I must bring about a positive result” deriving what is now known as Planck’s law (Figure 1) from Maxwell’s wave theory of light (Kragh, 2000). If Planck had thought more deeply about E=h*ν*, he might have noticed that it says energy lies on an alternative x-axis, shown along the top of Figure 1, but spectral radiance on the y-axis, as plotted, is also a function of energy—something that is not quite right, as discussed below. Planck was too wrapped up in the mathematics, to think carefully about the physics.

Excellent mathematics does not require good physics

Physics is the study of Nature, how matter and radiation behave, move, and interact throughout space and time. Mathematics, on the other hand, is logical deductive reasoning based on initial assumptions. Good mathematics is required to do excellent physics, but good physics is not required to do excellent mathematics. Excellent mathematics can be built on assumptions that may or may not be what is actually happening physically. Excellent mathematics can take you in logical directions that are not physically possible even though the mathematics is done in a rigorous and internally consistent way. There are often many different systems of mathematics that can describe one physical phenomenon, but which of these systems describes most accurately what is actually happening physically?

Maxwell (1865) introduced a mathematics of electromagnetic radiation assuming it propagates as waves. Planck (1901) stumbled empirically onto an equation that predicted observed values of radiance precisely and worked very hard to derive this equation from Maxwell’s mathematics rather than trying to understand what was physically happening. In so doing, he had to assume E=h*ν*, but he never stopped to think what this simple equation actually means physically. He was obsessed with finding a mathematical derivation based on Maxwell’s wave theory. Einstein (1905b) then initiated a very different system of mathematics of EMR based on the photoelectric effect where he seemed to assume an electron must be knocked loose by a quantum of light, billiard-ball style.

Ever since, experiments have been designed, interpreted, and documented assuming that EMR travels through space either as waves or as photons (Falkenburg, 2010). Both systems of mathematics have become highly developed, building on their initial assumptions, trying to fit each theory to increasingly complex experimental data.

Physicists to this day, think in terms of wave-particle duality, where they utilize whichever mathematics seems most appropriate to solve the problem at hand. The only two options on the table have been waves or particles.

In terms of basic logic, if you have a piece of fruit that is sort of like a banana (wave) and sort of like an orange (particle), it is clearly not equal to either.

Thermal energy in matter is well known to be a broad spectrum of frequencies of oscillation of all the bonds that hold matter together. It is the motion of charge caused by these oscillations on the surface of matter that appears to induce EMR, yet I cannot find anyone, in the history of physics, who seriously considered EMR simply to be a broad spectrum of frequencies of oscillation. Thinking about EMR, experimenting with EMR, expanding equations describing EMR have all been based on the initial assumption, either a wave or a particle. These initial assumptions do not appear to have been seriously questioned. They were accepted as fact. Both seem to work. The emphasis, however, has been on the mathematics not on the physics—not on trying to understand precisely what is happening physically.

As quantum mechanics and quantum electrodynamics were being developed, numerous equations became less and less physically intuitive. The tradition, therefore, was established and written in most textbooks that, at the quantum level, things just are not physically intuitive. That is just the way it is. Get over it. As Richard Feynman is reputed to have said: “Shut up and calculate.” Yet physics is supposed to be about what is actually, physically happening in the real world around us.

Energy is a continuum because frequency is a continuum

$E=h\nu$ says that oscillatory energy of an atomic oscillator (E), at a specific frequency, is equal to a constant of proportionality (h) times that frequency of oscillation (ν). Frequency, in this case, is not the frequency of a wave calculated by Maxwell’s wave theory, which says frequency is equal to the velocity of light divided by wavelength. Frequency (ν) is the frequency of oscillation of an atomic oscillator, the oscillation of some degree of freedom of some bond holding matter together. $E=h\nu$ says that oscillatory frequency, times a scaling constant (h), <u>is</u> the actual energy. In other words, thermal energy in matter is simply oscillation of the bonds holding matter together. These oscillations on the surface of matter induce electromagnetic radiation through the motion of charge. This electromagnetic radiation transports these frequencies through air and space, increasing the amplitudes of oscillation of the bonds in the absorbing matter and thus increasing the temperature of the absorbing matter.

Frequency of electromagnetic radiation is well-known to be a continuum extending from extremely low frequency radio signals (<30 Hz) to extremely high frequency gamma rays (>10^{19} Hz). If E=h*v* is correct, then a constant (h) times a continuum (*v*) must also be a continuum ranging from <10^{-13} to >10^{5} electronvolts (eV), more than 18 orders of magnitude. Therefore, microscopic electromagnetic energy is not quantized as almost universally assumed.

To be crystal clear on this very important point, E=h*v*, thought of as the "energy element," the "light quantum," the quantized particle of light, the photon, actually says that radiant energy at the microscopic level is a continuum—it is not quantized because frequency (*v*) is not quantized.

E=h*v* does appear to be a valid description of physical reality. Every description of the electromagnetic spectrum uses this equation to show how energy increases with increasing frequency from radio signals to microwaves, to infrared radiation, to visible light, to ultraviolet radiation, to X-rays, to gamma rays.

Thermal energy is a broad spectrum of frequencies

The bonds that hold matter together are not rigid. Every degree of freedom of every bond is observed to oscillate in a manner approximated by a Morse potential energy function (Figure 2) between a short length determined by the repulsion of like charges pushed together and a longer length determined by the attraction of opposite charges pulled apart. These oscillations are very high frequency, typically measured as trillions of cycles per second, terahertz (THz). These frequencies are so high and occur over such short atomic distances that we cannot perceive them as oscillations, but we do

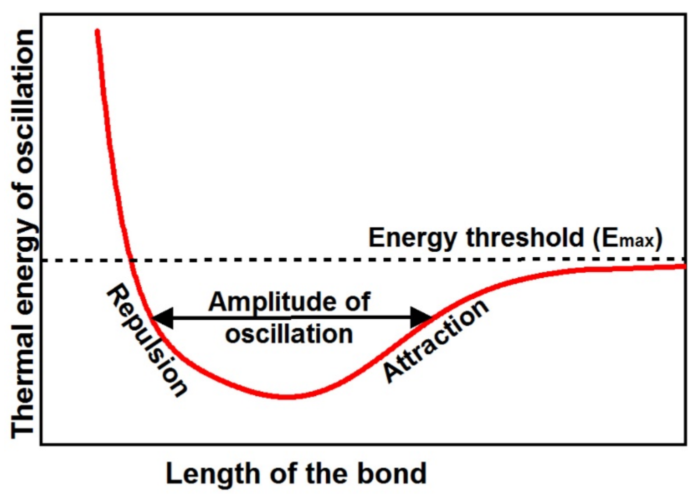

Figure 2. Each bond holding matter together oscillates between electrostatic forces of repulsion on the left and electrostatic forces of attraction on the right. Amplitude of oscillation increases as thermal energy increases. The bond comes apart when thermal energy equals E_{max}. This relationship is known as the Morse potential energy function.

perceive them as the energy necessary to cause chemical reactions, such as the photoelectric effect, dissociation, or ionization. We also perceive them as color in the visible spectrum, and we perceive a broad spectrum of these oscillations as heat flowing to produce temperature.

As a body of matter is cooled, the amplitude of oscillation at every frequency decreases (Figure 1); as a body is heated, the amplitude of oscillation at every frequency increases. At some energy threshold (E_{max}) (Figure 2), some frequency threshold ($\nu_{max}=E_{max}/h$), the amplitude of oscillation will become large enough for the bond to come apart, to dissociate. Plus, as absolute temperature approaches zero, the amplitude of oscillation, the motion of charge, and, therefore, thermal energy will all approach zero.

It is these oscillations of charge on the surface of matter that induce an electric field, that induces a magnetic field, that induces an electric field, and so on, providing a means of radiating these oscillations through air or space. If there were no oscillation of charge, electric and magnetic fields would not exist—radiation would not exist. It is these oscillations that create the electromagnetic field and it is the electromagnetic field that propagates these oscillations through air and space. One could say, in a slight twist of fate, that it is the interaction between electric and magnetic fields that provides the "luminiferous aether," the physical means to propagate electromagnetic radiation (light), in the form of frequency and amplitude of oscillation, through air and space.

It is also the very short but finite time it takes for this interaction between electric and magnetic fields that determines the velocity of light and why it is a constant. Even Maxwell concluded that the velocity of light was equal to one divided by the square root of the product of two constants: the vacuum permittivity (the resistance to forming an electric field) times the magnetic permeability (the ability to form a magnetic field) (Maxwell, 1873).

Planck's law (Figure 1) describes the distribution of measured radiance as a function of frequency, clearly reflecting the distribution of frequencies and amplitudes of oscillation on the surface of radiating matter. Note that as we heat matter, the amplitudes of oscillation get larger at every frequency. On the other hand, if we increase the amplitudes of oscillation at every frequency, the body of matter will get warmer. We can heat matter by increasing the amplitudes of oscillation within a narrow band of frequencies, but when the matter has reached thermal equilibrium as the result of conduction, Planck curves (Figure 1) show that the amplitude of oscillation will have increased at every frequency and especially at the highest frequencies in a very predictable way. Given the temperature of a body, a Planck curve defines what the radiance, intensity, brightness of the radiation will be at each frequency.

Heat capacity and storage of thermal energy

Thermal energy is stored in the bonds holding matter together. The capacity of a given material to absorb and store heat is observed to increase with the number of degrees of freedom of oscillation (Grossman, 2014). A simplistic way of looking at an oscillating bond in macroscopic, classical terms, ignoring acceleration and deceleration, is that the atoms move apart with a velocity v and thus a kinetic energy of $\frac{1}{2}mv^2$ and then move together with a similar kinetic energy of $\frac{1}{2}mv^2$, for a total kinetic energy per cycle of $E=mv^2$. The velocities are extremely high.

If these velocities approach the speed of light (c), then $E=mc^2$. This now famous equation, introduced by Einstein (1905a), emphasizes that a very small amount of mass contains a very large amount of bond energy. The energy per unit mass contained in all the bonds that hold matter together is equal to a very large number (nearly 3×10^8 meters per second) squared. This energy is stored in the bonds and is not accessible until a bond is broken. When a molecule of oxygen, for example, is dissociated by absorbing radiation with frequency >= 1237 THz, the two atoms of oxygen fly apart at very high velocity releasing 5.11 eV of energy as temperature, since temperature of a gas is proportional to the average velocity squared of all the atoms and molecules making up the gas. This explains why nuclear reactions are associated with such high temperatures and why an exponentially growing nuclear chain reaction breaking the bonds holding the nucleus of atoms together can become an awesome weapon of mass destruction, an atomic bomb.

The Planck constant

For $E=h\nu$, setting ν equal to one cycle per second shows that h is equal to the energy contained in one cycle per second. Planck’s constant (h) is normally specified today in units of energy seconds, but it actually, physically, is energy per cycle per second, which is equal to energy seconds divided by cycles. Omitting the unit cycles, which is customary, discards the reality that the energy we are talking about is oscillatory energy measured in cycles per second.

In the macroscopic world, energy is classically defined mechanically as the ability of a system to do work. Thus, for example, one joule is defined as the energy required to move an object one meter against a force of one newton. One electronvolt is the amount of energy gained or lost by the charge of a single electron moving across an electric potential difference of one volt. The Planck constant (h) scales the frequency of microscopic atomic oscillations to macroscopic mechanical energy so that we can apply the law of conservation of energy. The Planck constant (h), therefore, is a bridge between macroscopic and microscopic physics in the same manner as the Boltzmann constant (k_B). Note in Figure 1 that the exponent in the exponential term of Planck's law is $h\nu/k_BT$ where T is absolute temperature. This is the ratio, at the microscopic level, of energy as a function of frequency of oscillation ($h\nu$) divided by energy as a function of temperature (k_BT).

Normal modes of oscillation

Planck's postulate is typically stated as $E=nh\nu$, where total energy is the sum of n energy elements, all with the same energy, or $E=h(\nu_1+\nu_2+\nu_3+ \ldots . \nu_n)$. While this equation makes perfect sense mathematically, it makes no sense physically to add frequencies of light together. When you put 20 red lights next to each other, you still have red light, which, depending on the shade of red, has a level of energy between 1.65 to 2 eV. With 20 lights, you just have a greater amount (intensity) of this red-light level of energy. When you place a red light next to a blue light, you do not form ultraviolet light. You simply have some red light coexisting with some blue light (Figure 3). Frequencies of light, frequencies of electromagnetic radiation, are not additive because they do not physically interact with each other in any way in air or space, even over galactic distances, until in the immediate presence of matter. It is the bonds holding matter together that physically allow this interaction.

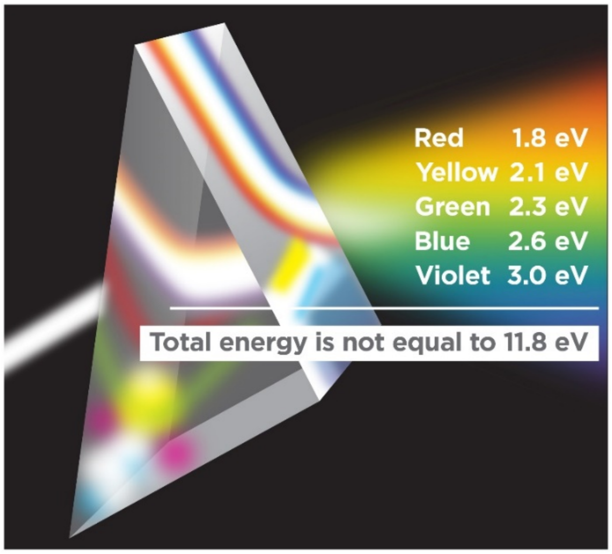

Figure 3. White light entering from the left is spatially separated by a prism into its component colors. The total energy contained in white light is not the sum of the energies of the colors (frequencies) that it contains. White light contains visible energies ranging from 1.65 to 3.26 eV (eV). Summing discrete component energies yields 11.8 eV, an energy level that is characteristic of ultraviolet-C radiation, which is well outside the actual distribution of energies.

$E=h(n\nu)$, however, does make perfect physical sense where, for a harmonic oscillator, n designates integer overtones and each overtone has a higher frequency which, therefore, has a higher level of energy. Atomic oscillators are anharmonic because the force of repulsion rises steeply with decreasing distance while the force of attraction decreases much more slowly with increasing distance (Figure 2). Thus n becomes (n+½) or some other non-integer value designating normal modes of anharmonic oscillation. It is not necessary to invoke electrons changing orbits to explain observed changes in energy levels. These different energy levels appear simply to be normal modes of oscillation of a bond holding matter together.

Good physics requires good mathematics, but good mathematics does not require good physics. There are many derivations and actions that make perfect sense in mathematics, such as adding frequencies of light, that are not physically possible—that do not occur in Nature.

Energy is transferred primarily by resonance

Bond oscillations are frictionless so that energy is added to or subtracted from the bond primarily by resonance. When the amplitude of oscillation at a specific frequency of one bond is larger than the amplitude of oscillation at the same frequency of an adjacent bond, the bond with the larger amplitude will “give up” amplitude to the bond with the smaller amplitude of oscillation until the amplitudes for both bonds are equal. Within extended matter, held together by bonds, conduction provides ways to share thermal energy among frequencies so that a smooth Planck curve (Figure 1) can be approached at thermal equilibrium. When a gas molecule absorbs energy from an electromagnetic field, however, the only energy transferred is at the resonant frequencies of all the normal modes, of all the degrees of freedom, of all the bonds holding the molecule together. These spectral lines of energy transferred are well observed and tabulated (Rothman et al., 2013) and are used by spectral physicists to identify the chemical nature of molecules close at hand and throughout the universe.

Thermal energy, transferred by resonance, moves spontaneously only from higher amplitude to lower amplitude at each frequency, which is from higher temperature to lower temperature (Figure 1) as stated by the second law of thermodynamics. Resonance sets the arrow of time from higher to lower amplitude of oscillation at each frequency and explains why the second law of thermodynamics in inviolable. The rate of energy transfer increases with increasing difference in amplitudes as is widely observed.

Spooky action at a distance

Every molecule of everything you see is oscillating primarily at some frequency (color) with some amplitude (brightness). When you look in the direction of that molecule with clear line of sight, the oscillations of that molecule cause three different types of cones in your eyes to resonate. Each type of cone is most responsive to a narrow band of frequencies often referred to as red, green, and blue bands. Our brains then turn the responses of these three types of cones into our perception of the color of that molecule. Our eyes are most responsive to the visible spectrum of frequencies because the size of cells making up the cones resonate best within the narrow range of visible frequencies (430 to 770 THz). Our cornea and lens decrease the sensitivity of our eye to ultraviolet light, protecting our cones under normal circumstances from damage by this higher-frequency, higher-energy radiation. Similarly, frequencies of changes in air pressure cause the cilia in our ears to resonate, allowing us to hear. We sense the physical world around us primarily through resonance.

The observation that oscillations of a molecule over there causes similar oscillations of cells over here, without anything visible connecting the molecule to the cells, is what Albert Einstein called “spooky actions at a distance” (Born et al., 1971, p. 155). The spooky action Einstein is referring to had become known twelve years earlier in quantum mechanics as quantum entanglement (Schrödinger, 1935), which has taken on a rich set of mathematical concepts trying to explain electromagnetic radiation in terms of photons. Recognizing that radiation is a continuum in frequency rather than photons, that radiation “propagates” by resonance, and that the resonant interaction ceases when matter in the measuring device is inserted in between, breaking the line of sight, raises the intriguing possibility that the mathematical formalism of quantum entanglement may not be physically correct—may not explain what is physically happening. Oscillations on the surface of the antenna of a radio transmitter are received by a radio receiver, within line of sight, when that receiver is tuned to resonate at the precise frequency transmitted. A molecule similarly oscillates at a specific color that causes any appropriate sensor within line of sight to resonate at the same frequency. This is why a crowd of people, each with their own sensors in their own eyes, all observe more or less the same thing when they are looking in the same direction.

“Spooky actions at a distance” are just a physical property of electromagnetic radiation traveling primarily as frequency enabling resonance.

Wavelike properties of light

Waves are the deformation of matter. Particles of matter are displaced and then restored to their normal resting place as a wave passes by. Energy of waves in matter is the work required to deform the medium through which the waves are travelling. There is no matter in space and Michelson and Morley (1887) showed that there is no luminiferous aether, something in space through which waves could travel. It is physically impossible for mechanical waves, as commonly defined, to propagate through air and space.

Electromagnetic radiation does exhibit wavelike properties, however, such as reflection, refraction, interference, and birefringence but only when the radiation interacts with matter. It is the bonds holding matter together that provide the means for frequencies of light to interact. In seismic or water waves, for example, motion at a specific location can be approximated by a Fourier series, the sum of a large, if not infinite, series of terms consisting of an amplitude times the sine and/or cosine of different wavelengths or frequencies. It is the bonds or pressure holding solid or liquid matter together that provide the physical basis for the plus signs, or "addability," in the Fourier series. Everything involved with mechanical waves is interconnected by bonds. Everything involved with electromagnetic radiation in air and space, on the other hand, is not connected and can be thought of as a Fourier series without plus signs—a series that is not additive. There is some red light, some blue light, some yellow light, etc., that do not interact until the full spectrum interacts with matter, as in a rainbow or prism (Figure 3) or in the classic double slit experiment (Young, 1802).

Energy in the macroscopic, mechanical world is typically a function of mass, a function of the extent of the matter involved, an *extensive* physical property of matter. *Extensive* properties are additive—more matter means more kinetic energy, more potential energy, etc. Thermal energy, however, is pervasive throughout matter at the microscopic molecular and atomic levels, is not a function of mass, and is, therefore, an *intensive* physical property that cannot be added together. This is the fundamental difference between the physics of the macroscopic and microscopic worlds.

Particle-like properties of light

The effects of light do display particle-like properties as a result of the photoelectric effect, dissociation, and ionization. Hertz (1887), Lenard (1902), and many others pieced together observations

1. that when certain frequencies of light shine on certain freshly-cut metal surfaces, electrons are released,
2. that doubling the intensity of the light doubles the number of electrons released but does not increase their energy, and
3. that no electrons are released if the frequency of the light is less than some value that differs for each type of metal.

These observations could not be explained by Maxwell's wave theory, but were explained by Einstein (1905b) assuming absorption of a "light quantum." The photoelectric effect is one of the strongest arguments for the existence of photons. Photomultipliers that utilize this effect are used widely throughout experimental physics to observe and measure the particle nature of light. It seems intuitively reasonable, that if an electron is emitted, it must have been hit, like a billiard ball, by a particle of light.

An alternative explanation, however, is that an electron is observed to be emitted when the frequency of oscillation is greater than ν_{max} (energy > E_{max}) for the Morse potential energy function (Figure 2) governing the electron. The photoelectric effect is observed for some metals using violet to ultraviolet frequencies in the range of 680 to 720 THz (2.8 to 3 eV). Similarly, a molecule of oxygen (O_2) is dissociated into two atoms of oxygen when illuminated with ultraviolet radiation with frequency >= 1237 THz (5.1 eV) and oxygen can be ionized by radiation with frequencies >= 2922 THz (12 eV).

There are many logical inconsistencies when thinking of photons as carriers of energy from a radiation source to a radiation absorber.

1. We can measure the presence of an electromagnetic field that is continuous in space and made up of a continuum of frequencies. What is the relationship of discrete photons to this field? Are there different photons for every frequency in the continuum?
2. Do photons in space interact with each other? If not, why not? Frequencies of EMR do not interact in space because there are no bonds across which they can interact.
3. Spectral physicists document in detail that gas molecules absorb energy only along spectral lines that are the resonant frequencies of the bonds holding the molecule together. Thus the spectrum of energy actually absorbed is determined by the molecule in the immediate vicinity of the molecule. How can these well-established observations be explained with photons?
4. How, precisely, is the energy transferred from a discrete photon to a specific gas molecule? Is it by collision? What happens if the photon only glances off the molecule?
5. How can photons diverging as they radiate from a very distant source, appear closely spaced from here on Earth?
6. How do photons interact physically with the human eye?

Photons are a very useful mathematical concept, but where is the evidence that they actually exist physically?

For more than 2500 years, since the time of Democritus and Aristotle in classic Greece, many of the most famous natural philosophers and physicists have argued about what is light (electromagnetic radiation) and whether light travels as a wave or as a particle. We do not see light; we only see the effects of light when it interacts with matter. Why do we persist in trying to describe light as either waves or as particles, things that we see? Doesn’t it seem reasonable that something we cannot see is not made up of something we can see? $E=h\nu$ says light, EMR, is simply frequency, something we cannot see until it interacts with matter. While frequency is something that we have a hard time visualizing because it is something that we cannot see, there does not seem to be any physical reason to invoke waves or particles as the physical nature of light.

Experimental verification

Based on calculations made by Albert Einstein in 1911, his theory of general relativity predicts that light from a distant star should be bent by Sun's gravity. Eddington (1920) confirmed this prediction during a solar eclipse on May 29, 1919, propelling Einstein to global fame. The same effect could be caused by light diffracted in the immediate presence of sun's massive amounts of matter just as a radio signal can be diffracted around a hilltop. Couldn't gravity simply be the very weak Coulomb force of attraction at the distant tail of the Morse potential energy function (Figure 2) that becomes significant only when at least one of the masses involved is very, very large? Gravity is an *extensive* physical property.

Verification of a prediction made on the basis of some theory, is a gold standard in physics. The value of a theory is established by whether the predictions made based on the theory can be observed. This is a very important standard of proof, but a successful prediction does not prove that the system of mathematics used to develop the theory describes what is actually, physically happening. There may be several systems of mathematics from which correct predictions can be made. This could explain why predictions of Einstein (1905b) about "light quanta" were all observed by Millikan (1916) in the laboratory.

Calculating radiative energy

Planck's law (Figure 1) describes observations made in the late 19th century, and still made today, measuring the *thermal effect* of radiation on a small piece of matter contained within the sensor, typically a thermopile or resistor—measuring how hot the matter becomes. Radiance on the y-axis in Figure 1 has units of watts per meter squared per steradian per hertz as a function of frequency on the x-axis. If $E=h\nu$, however, then energy is a function of frequency, energy is not additive, and energy should be plotted as an alternative x-axis shown at the top of Figure 1. The variable plotted on the y-axis should be the microscopic amplitude of oscillation, which is related to the brightness or intensity, and should not be a function of energy. Measuring amplitude of oscillation precisely was not easy in 1900 and is still not easy today. Planck's law needs to be reformulated based on laboratory measurements of amplitude of oscillation at each frequency of oscillation. This should not change the fundamental shape of each curve and the interrelationships of the family of curves.

If E=hν, current concepts and calculations of the total energy of radiation in units of watts per square meter are incorrect because watts are now a function of frequency so that radiant energy increases with increasing frequency. We need a new way of calculating *thermal effect*. The higher the frequency, the higher the temperature to which the absorbing body of matter will ultimately be raised, but how hot the absorbing body becomes is also a function of the intensity (amplitude of oscillation) at each frequency and the duration of exposure to the radiation. When the frequency of radiation is high enough to damage matter, the sensitivity of the matter to that frequency, the Radiative Amplification Factor, becomes important (Herman, 2010).

Towards a new understanding

In science, as in life, there are often several explanations for an observed event. There may be several different mathematical systems formulated to describe a specific observed physical phenomenon, but only one of these systems is likely to resemble most closely what is actually physically happening. The problem for the scientist is to determine which explanation is most likely the cause—which explanation makes the most physical sense. Often, in science, the simplest explanation prevails. For electromagnetic radiation (light), both the theory and mathematics based on frequency, that appear to be the most physically relevant, have not even been on the table, have not even been under consideration, or have been, at most, along the margins of consideration.

Maxwell (1865) assumed that radiation travels through space as waves. Even though Michelson and Morley (1887) showed that there is no luminiferous aether, that there is no way for waves to travel through space, the great success of Maxwell's equations in matter has caused most physicists, even today, to think of electromagnetic waves that travel through space in some special way that is not yet understood. Recognizing that electromagnetic radiation (light) travels through air and space simply as a broad spectrum of frequencies, that thermal energy at the atomic level equals a constant times frequency (E=hν), and that thermal energy is not additive, provides a much simpler, more logical, intuitive, and deterministic explanation for a broad range of physical observations currently addressed by quantum mechanics and quantum electrodynamics.

When quantum physics renounced the need to be physically intuitive, it went off into the world of mathematics, leaving physics behind—it renounced the need to be sure the mathematics described what was actually, physically happening. This led to designing, interpreting, and documenting physical experiments to prove the mathematics right (Falkenburg, 2010), and then to developing the mathematics in complex ways to make a square peg fit into a round hole—to make the favored theory able to explain the details of the experiments.

Quantum physics has been studied and developed intensely over the past century by some of the brightest minds in the world and in many cases explains observations to more than 10 decimal places. Much of the insight gained through quantum physics, when interpreted under these new and simpler realizations, may well move us closer to a theory of everything.

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