Matter and Light

The word *universe* is normally taken to mean everything that exists. The most obvious components of the universe are matter and light. By the end of the nineteenth century, is was known that light is simply one form of electromagnetic radiation, which also includes radio waves, infrared and ultraviolet light, X-rays, and gamma rays. The matter that we are most familiar with consists of the chemical elements in the form of atoms, which are composed of protons, neutrons, and electrons. Surprisingly, the chemical elements make up just a small part of the matter of the universe, most of which is in the form of a mysterious dark matter, a concept we will discuss in more detail in a later reading. Physical events are interactions that take place within the arena of space-time between matter and energy, one form of which is electromagnetic radiation.

Atoms

Empedocles was an ancient Greek philosopher who sometime around 450 BCE introduced the concept that all matter is made up, in differing proportions, of four elemental substances – earth, air, fire and water – and that the ratios of these affect the properties of the matter. Empedocles' theory was an important development in scientific thinking because it was the first to suggest that some substances that looked like pure materials, such as stone, were actually made up of a combination of different elements.

Democritus, some 30 years later, introduced the concept of atoms. Democritus taught that "nothing exists except atoms and the void: all else is mere opinion." He conceived of atoms as indivisible and eternal, and in fact the word *atom* is derived from the Greek word meaning "that which cannot be divided." The atoms of Democritus were small, discrete, and identical in composition, although they might differ in size and shape, with the differences in size and shape determining the specific properties of a substance. According to Democritus, perceived changes in the world were produced by changes in the groupings of atoms.

Aristotle accepted the theory of Empedocles but rejected that of Democritus. He argued that logic ruled out the concept of discrete atoms because the atoms of Democritus had extension in space and were identical in composition, but these properties are not compatible with indivisibility: Extension in space implies divisibility and composition implies yet smaller parts. Aristotle taught that matter is continuous rather than discrete in nature and that "everything continuous is divisible into divisibles that are infinitely divisible."

Despite philosophical differences, the concept of atoms was too persuasive to be dismissed, and by the seventeenth century most scientists, including Galileo and Newton, were atomists. In the early nineteenth century, the English chemist John Dalton used the concept to account for chemical reactions, placing atomic theory in a scientifically respectable context for the first time. By the end of the nineteenth century, the concept of the atom was well established, although some influential scientists at the time did not accept the atom as a real constituent of nature. It was not until the early twentieth century that an experiment suggested by Albert Einstein proved the existence of atoms.

Our current atomic theory is based on quantum mechanics and is a nonvisualizable model. Our best visualizable model is the planetary model with a tiny nucleus of protons and neutrons surrounded at a relatively great distance by electrons. The nucleus, though only a tiny fraction of the size of the atom, contains almost all of the mass of the atom. The atom is composed, overwhelmingly, of empty space. Ernest Rutherford, who suggested this model in 1911, referred to the nucleus as "a fly in a cathedral," a dimensionally correct analogy.

Protons are positively charged particles, and, as the name implies, neutrons are neutral, with no charge. These two types of particles have a tendency to bind together under the influence of the strong nuclear force. They have comparable masses, with the neutron being slightly more massive than the proton. The electron is a negatively charged particle that is only about one-two-thousandth the mass of the proton. It is not affected by the strong nuclear force, but it is attracted to the positively charged nucleus by the much weaker electromagnetic force. The combination of the strong nuclear force and the weaker electromagnetic force holds atoms together.

The Chemical Elements

A chemical element is any substance that cannot be broken down into simpler materials by chemical means. An atom is the smallest possible quantity of a chemical element. Hydrogen, oxygen, and iron are examples of common elements. In contrast, substances such as salt and water, on the other hand, can be broken down chemically, and they are called compounds. Compounds are composed of molecules, which are chemical combinations of atoms. For example, a water molecule is composed of two hydrogen atoms and one oxygen atom, and written as H_2O.

The nucleus of an atom is composed of neutrons and protons. The composition of the nucleus is described by an atomic number, Z, defined as the number of protons in the nucleus, and an atomic mass number, A, defined as the number of neutrons plus protons in the nucleus. If the atom is neutral, then there must be Z electrons in orbit around the nucleus to balance the positive charge of the nucleus. In many ways, the neutron and the proton behave as if they are two different states of the same particle. For this reason, the word nucleon is used to include both particles. Thus, the atomic mass number is the number of nucleons in the nucleus. The notation used to specify a particular nucleus is ${}^{A}_{Z}X$, where X represents the chemical symbol of the element. For example, the helium nucleus consisting of 2 protons and 2 neutrons is represented as ${}^{4}_{2}He$.

Each chemical element has a different number of protons in its nucleus. The number of protons determines the number of orbital electrons, which in turn determines the chemical properties of the element. The periodic table of the elements is arranged in order of increasing numbers of protons in the nucleus.

The Periodic Table of the Elements

Group → / ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
Lanthanides				57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides				89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

In 1913, the Danish physicist Niels Bohr modified the planetary model by suggesting that the electron orbits of the planetary model can have only certain allowed radii. That is, an electron can orbit the nucleus at certain allowed distances, but all radii between these allowed distances are forbidden. Each of the allowed orbits corresponded to a specific energy of the atom. Thus the energy of an atom, like the radius of the electron's orbit, is restricted. All intermediate energies are forbidden. The Bohr model of the atom was an extremely radical suggestion at the time. Not even Bohr himself could give any theoretical reason for why the electron orbits would be restricted in this way. His primary justification of this assumption was simply that it seemed to fit observed patterns in the properties of atoms, namely that each type of atom emitted or absorbed only certain energies of electromagnetic radiation.

Radioactive Decay

Some nuclei are inherently unstable. Their ratio of protons to neutrons is incorrect for the mass of the nucleus. In general, the heavier the nucleus is, the more neutrons relative to the number of protons are required for stability. For instance, a helium nucleus can be stable with two protons and two neutrons, but a lead nucleus with 82 protons requires something on the order of 126 neutrons to be stable. Nuclei with the wrong ratio for stability will respond either by ejecting a helium nucleus (alpha decay), changing a neutron into a proton (beta negative decay), or changing a proton into a neutron (beta positive decay). Sometimes a nucleus can have an appropriate neutron to proton ratio, but too much energy. In this case, the excess energy can be emitted in the form of electromagnetic radiation (gamma decay).

Radioactive decay occurs on a time scale that depends on the particular nucleus -- some almost immediately, others taking billions of years. The rate at which a particular radioactive nucleus decays is given by the half-life, or the time it takes one-half of the nuclei to decay. For example, carbon-14, a nucleus with six protons and eight neutrons, decays to nitrogen-14, a nucleus with seven protons and seven neutrons. Its half-life is 5,730 years. That is, in each interval of 5,730 years, half the remaining carbon-14 nuclei decay. Thus, after 11,460 years (two half-lives) only one-quarter of the original number of radioactive nuclei remain. After three half-lives, only one-eighth are left, and so on. Mathematically, this is called exponential decay.

Half-lives make it possible for radioactive substances to be used for dating. For example, potassium-40 decays to argon-40 with a half-life of 1.3 billion years. Argon-40 is a gas, so if a rock is melted, the argon is released into the atmosphere. Once it has re-solidified, any additional argon produced by radioactive decay will be trapped in the rock. In this way, the ratio of argon to potassium-40 is a direct measure of the time that has passed since the rock has solidified. For instance, if the ratio of argon to potassium-40 is exactly 3 to 1, then only one-quarter of the original potassium-40 remains and the rock must be exactly two half-lives, or 2.6 billion years, old. If the ratio is 3.7 to 1, the equation of exponential decay gives an age of 3.2 billion years. This technique, when applied to solar system rocks, indicates that the oldest ones (meteorite fragments of asteroids) are about 4.6 billion years old, and hence we estimate the age of the solar system to be about 4.6 billion years.

Electromagnetic Radiation

Essentially everything we know about the contents of the universe, and especially about objects beyond our solar system, is based on deciphering the information contained in the electromagnetic radiation emitted by those objects. We first knew about the stars in the sky because we saw them. As more powerful optical telescopes were built, we discovered additional kinds of objects in the sky. And in the last half of the twentieth century, we discovered still more of the contents of the universe through the use of telescopes that could "see" in other regions of the electromagnetic spectrum.

Questions about the nature of electromagnetic radiation began at least as far back as the ancient Greeks with their ideas about the nature of visible light. Various models were suggested, but it wasn't until the second half of the seventeenth century that the nature of light began to be formally debated among scientists. The one thing that was clear was that light could transfer energy from one place to another. For example, sunlight can heat water. Two schools of thought arose as to how this was accomplished.

Robert Hooke and Christian Huygens, contemporaries of Newton, proposed a wave model. According to this view, light was like sound. When one speaks, the vocal cords cause the air in the throat to oscillate, which causes the air near it to oscillate, and so on, until the air in the vicinity of the listener's eardrum oscillates. Each particle in the medium merely oscillates about some fixed position; there is no net transfer of air, just energy.

Isaac Newton objected to this model. He preferred the idea of particles moving through space from one material object to another. When one throws a baseball at a target, energy is transferred. In this same manner, Newton viewed light as a stream of tiny particles moving at high speeds, like bullets fired from a gun.

At the time, there was no experimental way to distinguish clearly between the wave model and the particle model. This situation began to change in the early part of the nineteenth century, when evidence began to accumulate in favor of the wave model. The apparent *coup de grace* to the particle theory was delivered in 1865 when James Clerk Maxwell, an English theoretical physicist, proposed his theory of electromagnetism. The theory suggested that electromagnetic disturbances could be propagated through space as waves. The theoretical speed of the waves was exactly that of the speed of light, which had been accurately measured some years earlier. The conclusion seemed unmistakable: light is not just a wave; specifically, it is an electromagnetic wave.

Maxwell's theory also made it clear that visible light was just part of an electromagnetic spectrum; that electromagnetic waves with wavelengths both longer and shorter than visible light should exist. Heinrich Hertz, the discoverer of one of these wavelengths, radio waves, said in 1889:

> We know that light is a wave motion. We know the speed of the waves, we know their length. In a word, we know completely the geometric relationships of this motion. These things no longer permit of any doubt, and a refutation of this view is unthinkable to the physicist. In so far as human beings can know the truth, the wave theory is a certainty.

Perhaps such a refutation was unthinkable to most, but not to Albert Einstein. In 1905, the same year he published his theory of relativity, his paper suggesting an experiment to prove the existence of atoms, as well as a paper on thermodynamics that earned him a doctorate from the University of Zurich, the then-23-year-old Einstein published a paper suggesting that in some situations, electromagnetic radiation would behave as if it were a stream of particles. To bolster his argument, he also suggested an experiment that would show this to be the case.

According to Einstein, electromagnetic radiation interacts with matter as discrete packets of energy, today called photons. The energy of a specific photon is associated with the wavelength of the radiation. Longer wavelengths correspond to lower photon energies and shorter wavelengths correspond to higher photon energies.

Experimental evidence soon indicated that Einstein was correct. Electromagnetic radiation did, in some instances, behave as if it were a stream of particles. But the evidence provided by the nineteenth century – that it behaved in other instances as if it were a wave – could not be ignored. However, the two models are mutually exclusive; there is no way to combine them into a single coherent model.

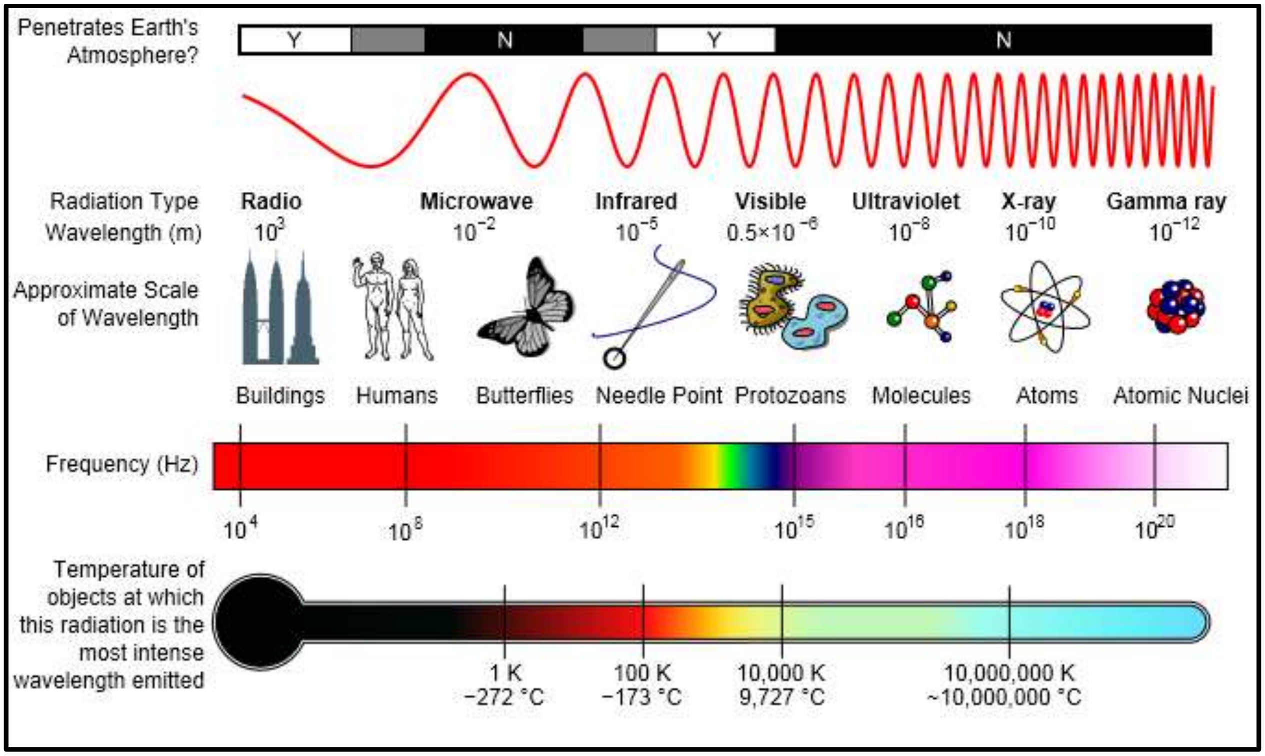
The resolution of this dilemma came by abandoning the effort to force electromagnetic radiation into one or the other model. Some phenomena have no analog in the world of everyday sensory experience. In that world, a clear distinction exists between waves and particles. Something is either a wave or a particle, not both. However, at the submicroscopic level, this distinction no longer exists. Thus, electromagnetic radiation is indisputably both wave-like and particle-like. This conclusion is referred to as wave-particle duality. Because there is nothing in everyday experience that exhibits this dualism, it is impossible to visualize the true nature of electromagnetic radiation. Thinking about a phenomenon for which there is no concrete analog can be an unsettling experience. As Einstein put it, "It is only with reluctance that one's desire for knowledge endures a dualism of this kind."

Scientists who must cope with this dilemma in their work take a pragmatic approach. They make use of one or the other model, depending on the situation. In some situations, it is more appropriate to treat radiant energy as a wave. To explain how electromagnetic radiation travels through space, the wave model is necessary. To explain how electromagnetic radiation delivers energy to matter, the particle model is necessary. Although this is a workable approach, one should not confuse these useful models with reality itself. In fact, electromagnetic radiation is more complex than depicted by either the wave or the particle model.

By the first decade of the twentieth century, physicists had discovered electromagnetic radiation in a wide range of wavelengths. At one end of the spectrum are radio waves, which have long wavelengths and low photon energy. At the other end are gamma rays, which have short wavelengths and high photon energy. All types of electromagnetic radiation travel through space at the speed of light.

Electromagnetic radiation can be produced in a number of different ways. The various regions of the electromagnetic spectrum are usually classified according to the way in which the radiation is produced. Radio waves are produced by oscillating electric currents. This part of the spectrum is subdivided according to the primary use of the radiation. Infrared, visible, and ultraviolet radiation is mostly produced by transitions of the outermost electrons of atoms as the atoms move from a higher to a lower energy state. X-rays are produced by the slowing of very high-speed electrons or by transitions of the inner orbital electrons of high-mass atoms. Gamma rays are emitted by the nuclei of atoms.

The distinction between infrared (below red), visible light, and ultraviolet (beyond violet) is based entirely on how the human eye responds to the radiation. Infrared radiation has wavelengths that are too long (or photons with too little energy) to excite the receptor cells in our eyes. Ultraviolet radiation has wavelengths that are too short (or photons with too much energy). The range of wavelengths within visible light correspond to the perceived colors we see. The longest-wavelength color of visible light is red, followed by orange, yellow, green, blue, and finally, violet, which has the shortest wavelength that can produce a visual response.



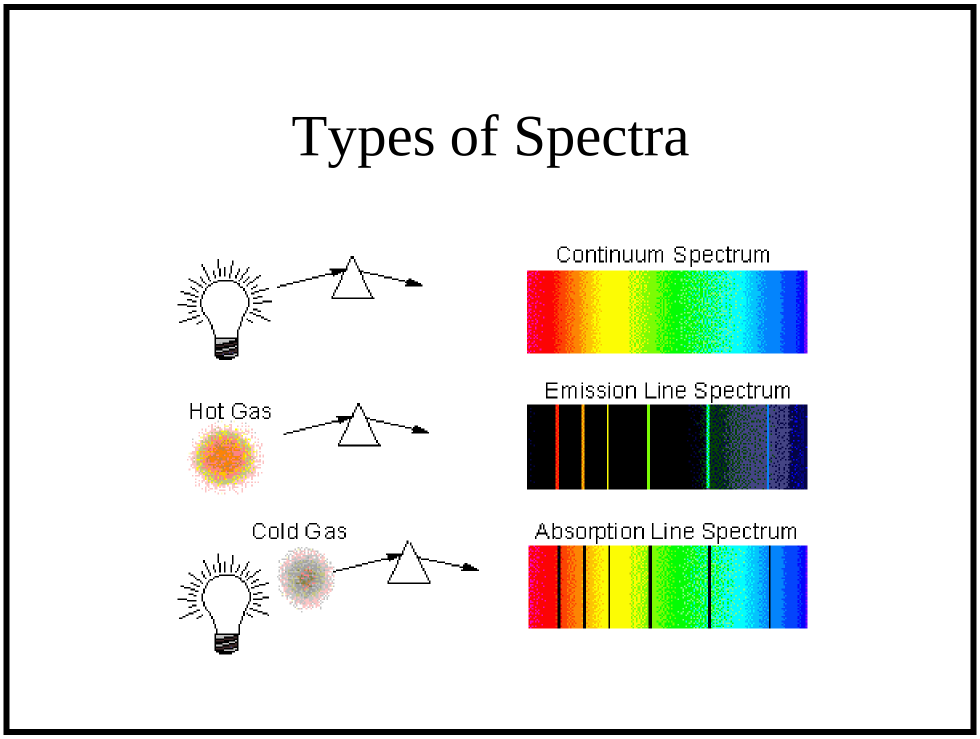
Atomic Spectra

Spectroscopy refers to the study of electromagnetic radiation based on the distribution of energy with respect to wavelength. A spectrometer is any device that will take incoming radiation and separate it on the basis of wavelength. A prism is an example of a spectrometer. If sunlight falls on a prism, the light emerging from the other side will appear as a rainbow. The longer-wavelength red light will come out at a slightly different angle than the shorter-wavelength violet light. When electromagnetic radiation from various sources is studied using a spectrometer, three distinct types of spectra are found. If all wavelengths within a certain range are present, the spectrum is a continuous spectrum. When only certain wavelengths are present, the spectrum is a bright-line spectrum. Finally, a dark-line spectrum is one in which almost all of the wavelengths are present, but certain ones are missing.

A continuous spectrum can be produced by a solid, a liquid, or a high-density gas. The total energy emitted and the distribution of this energy with respect to wavelength are determined by the temperature of the emitting object. The spectrum is independent of the chemical composition of the object. An example of this is the radiation emitted by an incandescent light bulb.

A bright-line spectrum is emitted by a hot, low-density gas. Unlike the continuous spectrum, it is completely determined by the chemical composition of the gas. Each chemical has its own distinctive bright-line spectrum. The spectrum identifies the element in the same way a fingerprint identifies an individual. The explanation for this is provided by the Bohr model, in which each type of atom has its own distinct set of allowed energy levels, so only certain photon energies can be emitted as the atom moves from a higher energy state to a lower energy state. A bright-line spectrum is also known as an emission spectrum. Examples of this type of spectrum include neon lights and the mercury-vapor lamps that are commonly used to illuminate parking lots.

A dark-line spectrum is produced when a continuous spectrum passes through a low-density gas. The wavelengths that are missing are, like those of the bright-line spectrum, and for the same reason, completely determined by the chemical composition of the low-density gas. In this case, however, the photons are being absorbed by the gas as the atoms move from a lower energy state to a higher energy state. An example of a dark-line spectrum is the radiation emitted by our sun and by other stars. Near the surface of our sun, a continuous spectrum is emitted. However, before exiting the surface of the sun, the radiation must pass through the sun's low-density atmosphere, where wavelengths are absorbed by the various chemical elements that make up our sun's composition.



An illustration of the types of spectra. Terms of use: The above illustration is attributed to Brown University and can be found at <http://astrophys-assist.com/educate/solarobs/ses01p11.htm>.

In the 1830s the positivist philosopher Auguste Comte was asked if there was anything science would never be able to determine. He gave what is almost certainly the right answer – yes – but then proceeded to give a now-disproven example, famously saying we could never know the chemical composition of the stars. Through an analysis of their absorption spectra, we now know their composition quite well.