The Nature of Light

Sir Isaac Newton (17th century) advocated the corpuscular theory of light. He thought that light consisted of a stream of tiny particles (corpuscles) emanating from a luminous object. This theory was able to explain rectilinear propagation (light moves in straight lines), reflection, and refraction. However, in order to explain refraction, the speed of light had to be faster in water than in air.

Christian Huygens (1690) advocated the wave theory of light. He thought light was actually a transverse wave. This theory was able to explain reflection, refraction and interference very easily as well as diffraction, which was studied in the early 1800's, but it could not explain rectilinear propagation. The fact that when a sound is made it can be heard in all directions. But light appears to travel in a beam and does not bend around obstructions instead it forms crisp shadows.

The debate between the corpuscular theory and the wave theory raged until Foucault's measurement of the speed of light in both air and water. Foucault found that light travels faster in air than in water, which disproved the corpuscular theory.

James Maxwell (1865) developed a series of mathematical equations from which he predicted that heat, light, and electricity are propagated in free space at the speed of light as electromagnetic disturbances. An electromagnetic wave is a periodic disturbance involving electric and magnetic fields, which are each at right angles to the direction of propagation. For instance, when light is traveling in the x-direction, the electric field may be oscillating in the y-direction, while the magnetic field may be oscillating in the z-direction. All of the energy is equally divided between the electric and magnetic field. This theory was able to explain all the properties of light such as rectilinear propagation, reflection, refraction, interference, and diffraction.

Heinrich Hertz a protégé of Maxwell set out to prove Maxwell's electromagnetic theory. He was able to experimentally confirm the mathematical relationships described by Maxwell's theory and show that light transmissions and electrically generated waves are of the same nature. However, in the process he also discovered the photoelectric effect in 1902. When two charged spheres are in the presence of light or other spark discharge, they are more likely to create a spark discharge is an example of the photoelectric effect, the emission of electrons by a substance when illuminated by electromagnetic radiation. The photoelectric effect was the one phenomenon that Maxwell's theory couldn't fully explain.

The modern view of light or quantum theory recognizes the dual character of light: radiant energy is transported in photons, which are guided along their path by a wave field. This theory encompasses portions of both the particle (photons) theory as well as the wave theory.

Diffraction is the bending of light around a barrier. For diffraction of light to occur, the wavelength of the light must be on the same order of magnitude as the width of the opening.

Double slit experiments are when light passes though two narrow slits. If white light is used, then it is separated into the colored bands. If monochromatic light is used, then alternating light and dark bands will be seen. (Grade level not responsible for calculations)

$$x = \frac{n\lambda L}{d}$$

Variable	Physical Quantity	Units
x	Distance to the nth order colored band from the central bright	Meters (m)
n	Order of the spectrum band	none
λ	Wavelength of light	Meters (m)
L	Distance from the slits to the screen	Meters (m)
d	Distance between the slits	Meters (m)

Example: ***Yellow-orange light from a sodium lamp of wavelength 590 nm is aimed at two slits separated by 1.50 x 10^{-5} m. What is the distance from the central line to the first-order yellow line if the screen is 1.40 m from the slits?***

Given	Formula	Substitution	Answer

Single slit experiments are when light is passed through a narrow single slit and a series of light and dark interference bands appear. You will have a central bright band with progressively less intense bright and dark bands appear on either side of the central bright.. (Grade level is not responsible for calculations)

$$x = \frac{n\lambda L}{w}$$

Variable	Physical Quantity	Units
x	Distance to the nth order colored band from the central bright	Meters (m)
n	Order of the spectrum band	none
λ	Wavelength of light	Meters (m)
L	Distance from the slit to the screen	Meters (m)
w	Width of the single slit	Meters (m)

Example: Light from a He-Ne laser (λ = 632.8 nm) falls on a slit of unknown width. A pattern is formed on a screen 2.5 m away on which the first dark band is 12.5 mm from the center of the central bright band. How wide is the slit?

Given	Formula	Substitution	Answer

Diffraction gratings Experiments are when light passes though multiple narrow slits and white light is separated into the spectral bands. (Grade level is not responsible for calculations). Using a diffraction grating, the emission spectrum for elements can be observed. Each element has a different emission spectrum. Light is emitted when an excited electron falls from a higher energy level to a lower energy level. Based on this spectral lines that are observed, the composition of starts is determined.

$$x = \frac{n\lambda L}{d} \quad \text{or} \quad \lambda = \frac{d \times \sin\theta}{n}$$

Variable	Physical Quantity	Units
x	Distance to the nth order colored band from the central bright	Meters (m)
n	Order of the spectrum band	none
λ	Wavelength of light	Meters (m)
L	Distance from the slits to the screen	Meters (m)
d	Distance between the slits	Meters (m)
θ	Angle of deviation	Degrees (°)

Example*: A diffraction grating has 8000 lines/cm. The grating is illuminated by a narrow beam of white light. (a) What is the angle between the incident beam and the violet image (λ = 400 nm)? (b) What is the angle between the incident beam and the third maxima?*

Given	Formula	Substitution	Answer

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Thin film interference such as what is seen in soap bubbles is produced by the constructive and destructive interference of light waves. Some of the light waves are reflected at the outer surface of the soap bubble and some of the light waves are reflected at the inner surface of the bubble film. The waves reflected back at the outer surface of the bubble are inverted when they are reflected since it occurred as the light was attempting to go into a denser medium. On the other hand, the light waves that were reflected at the inner surface are not inverted since it occurred as the light was attempting to go into a less dense medium. It is the interference between these out of phase reflected waves that creates the colors. Depending upon the thickness of the bubble, different wavelengths interfere constructively and destructively creating the mixture of colors.

According to the modern theory of light, there is a magnetic field oscillating in one dimension and an electric field oscillating in another direction, therefore the light itself can be thought of as oscillating in both of these dimensions simultaneously all the while traveling in the third dimension. A horizontally polarizing filter allows only the part of the wave that is oscillating in a horizontal direction to pass through and blocks out the portion, which was oscillating, in the vertical direction. The reverse is true for a vertical polarizer. Light that is polarized is only vibrating in one direction. Glare or light that has been reflected is polarized, this is the reason that polarized sunglasses reduce the glare.

White light is not a single color of light but a combination of the 3 primary colors of light. The primary colors of light are red, blue, and green unlike the primary colors of paint. The secondary colors are combinations of primary colors: red + blue = magenta, blue + green = cyan, and red + green = yellow. Complementary colors are two colors of light that can be added together to form white light, for example red and cyan.

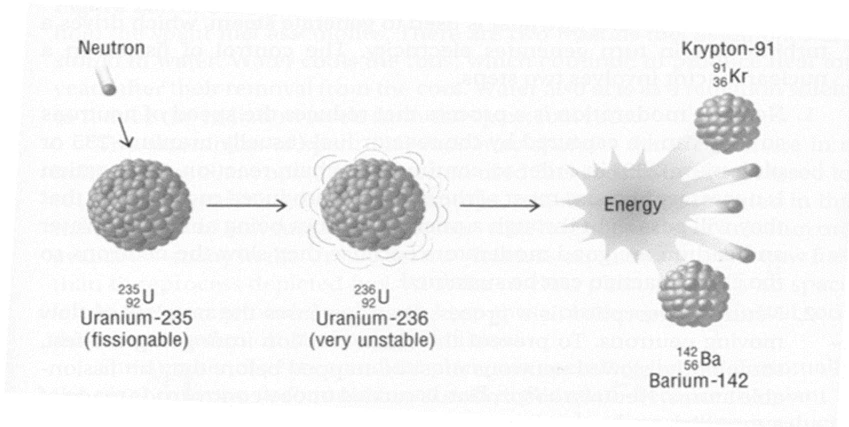
- Nuclear chemistry deals with the nuclei of atoms.
- Sometimes the nuclei of atoms are unstable – small parts break off and energy is released. This is called radioactive decay. In radioactive decay, mass is not lost. For instance Uranium 238 undergoes radioactive decay and forms Thorium 234 and releases an alpha particle. ${}^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$. Lead 210 on the other hand will undergo beta decay and forms Bismuth 210 and releases a beta particle. ${}^{210}_{82}Pb \rightarrow {}^{210}_{83}Bi + {}^{0}_{-1}e$
- Substances whose nuclei change spontaneously are called radioactive.
- Nuclear Radiation includes the emitted particles and energy.

Example: Radon 220 undergoes alpha decay to form Polonium 216. Write the equation for this radioactive decay.

Example: Bismuth 214 undergoes beta decay to form Polonium 214. Write the equation for this radioactive decay.

Radiation and radioactivity affect our lives in many ways:
- Solar radiation powers our food chain.
- Electromagnetic radiation constantly surrounds us.
- X-rays and other forms of radiation are used as tools.
- Nuclear energy provides electricity for many regions.

Nuclear Fission – the *splitting* of a nucleus into two smaller pieces (one usually a little bigger than the other) from being hit with a neutron.



- Nuclear fission releases a lot of energy. (1,000,000 times as much as any chemical reaction – at least).
- The energy released is most commonly converted into electricity (nuclear power plants)
- U-235 is the *only naturally* occurring isotope to undergo fission, but many synthetic nuclei can (U-233, Pu-239, and Cf-252).

Nuclear Fusion – Two smaller nuclei are *combined* (fused) to form a new, larger nucleus. This releases much more energy than fission, due to the conversion of mass to energy. In fusion, the binding energy per nucleon increases with increasing atomic number.

- Fusion powers the sun – Hydrogen atoms combine to form Helium.
- When elements combine in a fusion reaction, they eject particles called positrons – they are the same size as electrons, but have a positive charge : $^{0}_{+1}e$
- Fusion reactions occur at temps. in excess of 4 x 10^7 °C. At this temp, matter exists in the form of plasma.
- Fusion reactions also require a pressure greater than 1000 atms
- Fusion on the sun requires two β particles in addition to the four $^{1}_{1}H$ atoms.

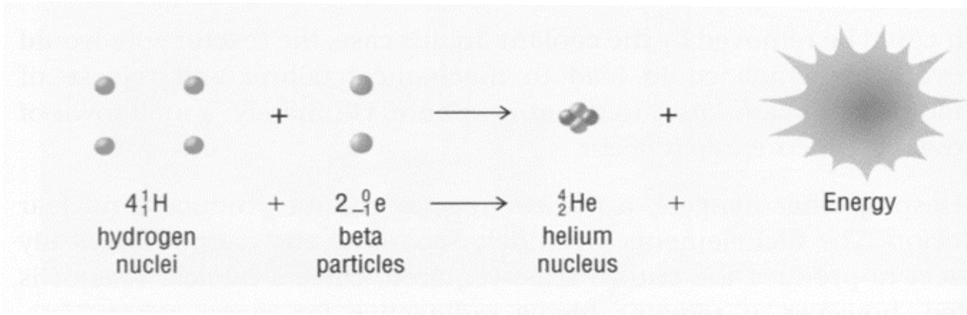
- Nuclear reactions are so powerful because a VERY small bit of mass is changed directly into a huge amount of energy...($E = mc^2$)...however, no overall change in mass is noted.

  - E = energy
  - m = mass
  - c = the speed of light (300,000,000 m/s)

- **Tracer** – Radioisotope with a short half-life that is placed inside the body to trace or locate abnormalities in body functions. (Ex. Iodine-131, Technetium-99m)
- Tracers are also used for non-medical uses including: carbon dating, and radioactive labeling.
- **Irradiation** - being hit with radiation from the outside. (ex. X-rays, MRI, laser surgery – incl. Cancer treatment)

Other uses for irradiation include:

1. **Food preservation – gamma irradiation is also used to kill bacteria, fungi, or molds on prepackaged foods. (ex. MRE's).**
2. **Sterilization of medical and scientific supplies, and medical waste. (goggle cabinet in the lab!)**



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Example:

How much energy is released when the mass defect of a reaction is 1 milligram?

Given	Formula	Substitution	Answer

As an eager young student of physics in the 1890s, Albert Einstein was troubled by a difference between Newton's laws of mechanics and Maxwell's laws of electromagnetism. Newton's laws were independent of the state of motion of an observer; Maxwell's laws were not—or so it seemed. Someone at rest and someone in motion would find that the same laws of mechanics apply to a moving object being studied, but they would find that different laws of electricity and magnetism apply to a moving charge being studied. Newton's laws suggest that there is no such thing as absolute motion; only relative motion matters. But Maxwell's laws seemed to suggest that motion is absolute.

In a celebrated 1905 paper titled “On the Electrodynamics of Moving Bodies,” written when he was 26, Einstein showed that Maxwell's laws can, after all, like Newton's laws, be interpreted as being independent of the state of motion of an observer—but at a cost! The cost of achieving this unified view of nature's laws is a total revolution in how we understand space and time.

Einstein showed that as the forces between electric charges are affected by motion, the very measurements of space and time are also affected by motion. All measurements of space and time depend on relative motion.

For example, the length of a rocket ship poised on its launching pad and the ticks of clocks within are found to change when the ship is set into motion at high speed. It has always been common sense that we change our position in space when we move, but Einstein flouted common sense and stated that in moving we also change our rate of proceeding into the future—time itself is altered. Einstein went on to show that a consequence of the interrelationship between space and time is an interrelationship between mass and energy, given by the famous equation $E = mc^2$.

These are the ideas that make up this topic—the ideas of special relativity— ideas so remote from your everyday experience that understanding them requires stretching your mind. It will be enough to become acquainted with these ideas, so be patient with yourself if you don't understand them right away. Perhaps in some future era when high-speed interstellar space travel is commonplace, our descendants will find that relativity makes common sense.

The speed of light in free space has the same measured value for all observers, regardless of the motion of the source or the motion of the observer; that is, the speed of light is a constant.

To illustrate the above statement, consider a rocket ship departing from the space station. A flash of light traveling at 300,000 kilometers per second, or *c*, is emitted from the station. Regardless of the velocity of the rocket, an observer in the rocket sees the flash of light pass her at the same speed *c*. If a flash is sent to the station from the moving rocket, observers on the station will measure the speed of the flash to be *c*. The speed of light is measured to be the same regardless of the speed of the source or receiver. *All* observers who measure the speed of light will find it has the same value *c*. The more you think about this, the more you think it doesn't make sense. This explanation has to do with the relationship between space and time.

Let's examine the notion that time can be stretched. Imagine that we are somehow able to observe a flash of light bouncing to and fro between a pair of parallel mirrors, like a ball bouncing to and fro between a floor and ceiling. If the distance between the mirrors is fixed, then the arrangement constitutes a *light clock*, because the back-and-forth trips of the flash take equal time intervals. Suppose this light clock is inside a transparent high-speed spaceship. An observer who travels along with the ship and watches the light clock sees the flash reflecting straight up and down between the two mirrors, just as it would if the spaceship were at rest. This observer sees no unusual effects. Note that, because the observer is in the ship moving along with it, there is no relative motion between the observer and the light clock; we say that the observer and the clock share the same reference frame in spacetime.

Suppose now that we are standing on the ground as the spaceship whizzes by us at high speed—say, half the speed of light. Things are quite different from our reference frame, for we do not see the light path as being simple up-and-down motion. Because each flash moves horizontally while it moves vertically between the two mirrors, we see the flash follow a diagonal path. From our Earthbound frame of reference the flash travels a *longer distance* as it makes one round trip between the mirrors, considerably longer than the distance it travels in the reference frame of the observer riding along with the ship. Because the speed of light is the same in all reference frames (Einstein's postulate), the flash must travel for a corresponding longer time between the mirrors in our frame than in the reference frame of the on-board observer. This follows from the definition of speed— distance divided by time. *The longer diagonal distance must be divided by a correspondingly longer time interval to yield an unvarying value for the speed of light*. This stretching out of time is called **time dilation.**

We have considered a light clock in our example, but the same is true for any kind of clock. All clocks run more slowly when moving than when at rest. Time dilation has to do not with the mechanics of clocks but with the nature of time itself.

The relationship of time dilation for different frames of reference in spacetime can be derived from Figure 35.10 with simple geometry and algebra. The relationship between the time t_0 (call it the *proper time*) in the frame of reference moving with the clock and the time *t* measured in another frame of reference (call it the *relative time*) is

$$t = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

where *v* represents the speed of the clock relative to the outside observer (the same as the relative speed of the two observers) and *c* is the speed of light. The quantity $1 - v^2/c^2$ is the same factor used by Lorentz to explain length contraction. We call the inverse of this quantity the *Lorentz factor* γ.

(gamma). That is $$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$ Then we can express the time dilation equation more simply as $$t = \gamma t_0$$
Let's look at the terms in γ. Some mental tinkering will show that γ is always greater than 1 for any speed *v* greater than zero. Note that since speed v is always less than *c*, the ratio *v/c* is always less than 1; likewise for v^2/c^2. Can you see it follows that γ is greater than 1? Now consider the case where $v = 0$. This ratiov^2/c^2 is zero, and for everyday speeds where v is negligibly small compared to *c*, it's practically zero. Then $1 - (v^2/c^2)$ has a value of 1, as has which makes γ = 1. Then we find that $t = t_0$—time intervals appear the same in both reference frames. For higher speeds, *v/c* is between zero and 1, and $1 - (v^2/c^2)$ is less than 1; likewise, This makes γ greater than 1, so t_0 multiplied by a factor greater than 1 produces a value greater than t_0—an elongation—a dilation of time.

To consider some numerical values, assume that *v* is 50% the speed of light. Then we substitute 0.5*c* for *v* in the time-dilation equation and after some arithmetic find that γ = 1.15; so $t = 1.15\ t_0$. This means that if we viewed a clock on a spaceship traveling at half the speed of light, we would see the second hand take 1.15 minutes to make a revolution, whereas an observer riding with the clock would see it take 1 minute. If the spaceship passes us at 87% the speed of light, γ = 2 and $t = 2t_0$. We would measure time events on the spaceship taking twice the usual intervals, for the hands of a clock on the ship would turn only half as fast as those on our own clock. Events on the ship would seem to take place in slow motion. At 99.5% the speed of light, γ = 10 and $t = 10\ t_0$; we would see the second hand of the spaceship's clock take 10 minutes to sweep through a revolution requiring 1 minute on our clock.

To put these figures another way, at 0.995 *c*, the moving clock would appear to run a tenth of our rate; it would tick only 6 seconds while our clock ticks 60 seconds. At 0.87 *c*, the moving clock ticks at half rate and shows 30 seconds to our 60 seconds; at 0.50 *c*, the moving clock ticks 1/1.15 as fast and ticks 52 seconds to our 60 seconds. Moving clocks run slow.

Nothing is unusual about a moving clock itself; it is simply ticking to the rhythm of a different time. The faster a clock moves, the slower it appears to run as viewed by an observer not moving with the clock. If it were possible to make a clock fly by us at the speed of light, the clock would not appear to be running at all. We would measure the interval between ticks to be infinite. The clock would be ageless! If we could move with such an imaginary clock, however, the clock would not show any slowing down of time. To us the clock would be operating normally. This is because there would be no motion of the clock relative to us. The v in γ would then be zero, and $t = t_0$; we and the clock would share the same frame in spacetime.

If a person whizzing past us checked a clock in our reference frame, he would find our clock to be running as slowly as we find his to be. We each see each other's clock running slow. There is really no contradiction here, for it is physically impossible for two observers in relative motion to refer to one and the same realm of spacetime. The measurements made in one realm of spacetime need not agree with the measurements made in another realm of spacetime. The measurement that all observers always agree on, however, is the speed of light.

Time dilation has been confirmed in the laboratory innumerable times with particle accelerators. The lifetimes of fast-moving radioactive particles increase as the speed goes up, and the amount of increase is just what Einstein's equation predicts.

Time dilation has been confirmed also for not-so-fast motion. In 1971, to test Einstein's theory, four cesium-beam atomic clocks were twice flown on regularly scheduled commercial jet flights around the world, once eastward and once westward, to test Einstein's theory of relativity with macroscopic clocks. The clocks indicated different times after their round trips. Relative to the atomic time scale of the U.S. Naval Observatory, the observed time differences, in billionths of a second, were in accord with Einstein's prediction. Now, with atomic clocks orbiting the Earth as part of the global positioning system, adjustments for the effects of time dilation are essential in order to use signals from the clocks to pinpoint locations on Earth.

This all seems very strange to us only because it is not our common experience to deal with measurements made at relativistic speeds or atomic-clock-type measurements at ordinary speeds. The theory of relativity does not make common sense. But common sense, according to Einstein, is that layer of prejudices laid down in the mind prior to the age of 18. If we spent our youth zapping through the universe in high-speed spaceships, we would probably be quite comfortable with the results of relativity.

As objects move through spacetime, space as well as time changes. In a nutshell, space is contracted, making the objects look shorter when they move by us at relativistic speeds. This **length contraction** was first proposed by the physicist George F. FitzGerald and mathematically expressed by another physicist, Hendrick A. Lorentz (mentioned earlier). Whereas these physicists hypothesized that matter contracts, Einstein saw that what contracts is space itself. Nevertheless, because Einstein's formula is the same as Lorentz's, we call the effect the *Lorentz contraction*: $L = L_0\sqrt{1 - \frac{v^2}{c^2}}$ where v is the relative velocity between the observed object and the observer, c is the speed of light, L is the measured length of the moving object, and L_0 is the measured length of the object at rest.

Suppose an object is at rest so that $v = 0$. When we substitute $v = 0$ in the Lorentz equation, we find $L = L_0$, as we would expect. When we substitute various large values of v in the Lorentz equation, we begin to see the calculated L get smaller and smaller. At 87% of c, an object would be contracted to half its original length. At 99.5% of c, it would contract to one-tenth its original length. If the object were somehow able to move at c, its length would be zero. This is one of the reasons we say that the speed of light is the upper limit for the speed of any moving object.

Length contraction should be of considerable interest to space voyagers. The center of our Milky Way galaxy is 25,000 light-years away. Does this mean that if we traveled in that direction at the speed of light it would take 25,000 years to get there? From an Earth frame of reference, yes, but to the space voyagers, decidedly not! At the speed of light, the 25,000-light-year distance would be contracted to no distance at all. Space voyagers would arrive there instantly!

For hypothetical travel near the speed of light, length contraction and time dilation are just two faces of the same phenomenon. If astronauts go so fast that they find the distance to the nearest star to be just one light-year instead of the four light-years measured from Earth, they make the trip in a little more than one year. But observers back on Earth say that the clocks aboard the spaceship have slowed so much that they tick off only one year in four years of earth time. Both agree on what happens: The astronauts are only a little more than a year older when they reach the star. One set of observers say it's because of length contraction, the other set say it's because of time dilation. Both are right.

If space voyagers are ever able to boost themselves to relativistic speeds, they will find distant parts of the universe drawn closer by space contraction, while observers back on Earth will see the astronauts covering more distance because they age more slowly.