Week 12

Physics 1409/1430 – Physics 2

Hello and Welcome to the weekly resources for PHY 1409/1430 – Physics 2!

This week is Week 12 of classes, and typically in this week of the semester, your professors are covering these topics below. If you do not see the topics your particular section of class is learning this week, please take a look at other weekly resources listed on our website for additional topics throughout the semester.

We also invite you to take a look at the group tutoring chart on our website to see if this course has a group tutoring session offered this semester.

If you have any questions about these study guides, group tutoring sessions, private 30-minute tutoring appointments, the Baylor Tutoring YouTube channel or any tutoring services we offer, please visit our website www.baylor.edu/tutoring or call our drop in center during open business hours, M-Th 9am-8pm on class days, at 254-710-4135.

Important Information

Important Conventions

Keywords: Special Relativity, Mass and Energy, Photoelectric Effect, Bohr Model

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Special Relativity

Special relativity is a part of the theory of Relativity, the work of one of the greatest minds in history, AlbertEinstein. In special relativity, you only deal with inertial reference frames.

All the natural laws of physics are valid in inertial frame, the caveat is that the reference frame moves at a constant velocity. Hence, they do not accelerate. What is going to be the focus here is comparing two reference frames. When you are dealing with relativity, you are going to imagine yourself in the shoes of two observers in two different reference frames. This section is all about perspective. An easy example would be imagining the world to someone in a moving car and compare it to someone stationary outside the car. To the person in the car, the world around them is moving if they are unaware, they are in a car but for the observer outside

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the car, the car is in motion.

This topic is going to seem very confusing. The trick is to take it slow and go one step at a time. But it is completely normal to feel frustrated!

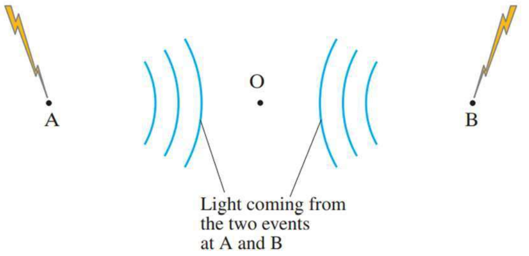
There are two immutable postulates when you are considering special relativity that must always be kept in mind.

1. (Relativity Principle) The laws of physics have the same effect in all inertial reference frame, i.e., there is no way for an observer in a reference frame to know whether the reference frame is moving or is stationary.
2. The speed of light is the same for all reference frames, irrespective of the speed of the source or observer.

These two rules form the foundation of special relativity. Using these rules, we compare weird scenario.

Simultaneity

In special relativity, we discover that the concept of simultaneous events is observer relative, which means that whether two events are truly simultaneous is dependent on where the observer is when the events occur. This phenomenon is due to the 2nd postulate. Since the speed of light is the same in all reference frames, it acts as the universal speed limit. If an observer is not equidistant from two events but see them occur simultaneously, then they could not have been simultaneous. The light from both events is travelling at the same speed. That means that they cover the same distance in the same amount of time. So, light from the farther event cannot reach an observer at same time as the light from the closer event, the light from the farther event needs



more time to get to the observer. Hence, the farther event has to occur earlier than the second event for the events to seem simultaneous to the observer. And if there was another observer who was moving relative to the first observer, that person would not see the events happen at the same time! Trippy right?!?!?!

Time Dilation and Length Contraction

Because the weirdness of simultaneity, does time really pass the same way in two different reference frames? The answer is no. For the reference frame that is moving relative to the observer, time stretches/expands/dilates. As there is a lag between the time an event occurred and an observer in different reference observing, the time interval between two events for an observer in a different reference frame (typically stationary) is greater than that for the observer in the reference of the event. This phenomenon is referred to as time dilation.

The main point of time dilation is to remember that time in a moving reference frame passes slower than the time passing in a stationary reference frame. The difference in the time interval can be calculated using the following formula.

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

The astounding thing is that time dilation is always occurring. It is happening every day. But it’s so small, we cannot observe it. The time dilation effect is only apparent when travelling at relativistic speeds (~0.9*speed of light). What is essential to keep track of when using the equation above is that Δt_0 is for the reference frame at rest, and Δt is for the moving reference frame.

Now, let’s consider distance. What if a moving reference frame covers a distance x. For the stationary frame, time t passes. But remember, for the moving reference frame, time is passing slowly. So, the time observed in the reference frame would be less than the time observed in the stationary frame. So, due to relativity, the two-reference frames also measure different distances. For the moving reference frame, length contracts. The length of an object in a moving reference frame is measured to be shorter. This phenomenon referred to be length contraction. We can calculate the change in length using the following formula.

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$$\ell = \ell_0\sqrt{1 - v^2/c^2}$$

Relativistic Mass, Momentum and Energy

As we saw above, the rules of mechanics change when you look at relativistic momentum. Due to this, we must also modify momentum to make sure it is conserved.

$$p = \frac{mv}{\sqrt{1 - v^2/c^2}} = \gamma mv$$

The gamma factor represents $1/\sqrt{1 - v^2/c^2}$ in the expression. Now, we know that the gamma factor does not affect the velocity in the expression as it represents the relativistic velocity of the moving frame, but what is does affect is mass. Hence, in relativity, a particle has a relativistic mass! The m represents the rest mass, meaning the mass when the object is not in motion. We can calculate relativistic mass using the following equation.

$$m_{\text{rel}} = \frac{m}{\sqrt{1 - v^2/c^2}}$$

This topic brings us to energy and perhaps the most well know equation in the world today. All particles have a rest energy, which is a definite constant that does not change. It is the energy due to existence as matter. Rest energy is represented by $E = mc^2$. Now, when the particles are in a moving reference frame, the energy changes. This energy it referred to as the total energy of the particle, which is just the product of the gamma factor and mc^2. The difference between the total energy and the rest energy is the kinetic energy, which is given by the following.

$$\text{KE} = \gamma mc^2 - mc^2 = (\gamma - 1)mc^2$$

These topics consisted of a lot of interesting and confusing information. But they are only a small part of the theory of relativity, which continues to be proven right decades after its proposal. Now let’s look at the work that got Einstein his Nobel Prize, the Photoelectric Effect.

Einstein broke the assumption that energy is a continuous value, which had been the assumption for quite some time. This change in theory was necessary due to the observation of blackbody radiation and the proposition of Plank’s quantum hypothesis to explain the behavior. Einstein ultimately arrived at the conclusion that energy is quantized, consisting of

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distinct packets of energy that occur at particular intervals. He used this proposition and extended it to light. Since energy is quantized, light must consist of packets of energy, like tiny particles, which we now call photons. The frequency of the wave determines the magnitude of the energy packets, calculated using

$$E = hf$$

The h stands for the Plank's constant. Using this extension, Einstein explained the photoelectric effect.

When light hits a metal surface, it causes electrons to be emitted from the surface. This phenomenon is referred to as the photoelectric effect. The electrons require a minimum amount of energy to be knocked out of the metal atoms' outer orbitals. This energy is called the work function(W_0). So based on the principles above, Einstein proposed the photon theory, which makes the following predictions:

1. An increase in intensity of light will cause more electrons to be emitted but as long as the frequency of the light remains the same, the kinetic energy of the electrons remains the same.
2. If frequency of light increases, the KE of the electrons emitted increases linearly.
3. If the energy of the photons is less than the work function, no electrons are emitted.

Based on this, the following equation was derived for the photoelectric effect.

$$\mathrm{KE}_{\mathrm{max}} = hf - W_0$$

The above predictions were proven right through experimentation, and Einstein won a NobelPrize for his work on the photoelectric effect.

Energy and Momentum of Photon

Since photon travel at the speed of light, they are relativistic. But that would mean that their mass goes to infinity. Hence, to avoid infinite momentum, it is assumed that the mass of a photon is 0. With this assumption, the expression for its energy and momentum are derived.

$$\mathrm{KE} = hf \qquad p = \frac{h}{\lambda}$$

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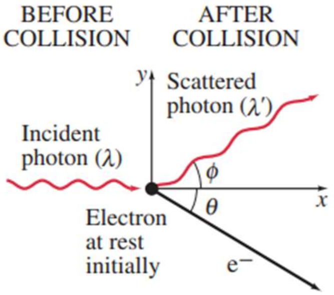
Photon Interactions:

There are 4 major types of interactions photons can have:

1. A photon can knock an electron out of an atom. (Photoelectric effect)
2. A photon can collide with an electron in an atom and excite it to a higher energy state, creating an atom in an excited state.
3. A photon can collide with an electron and not lose all its energy like the 2 above. Here, the photons get knocked of the original path, losing some energy. The speed of the photon will still be c but it will have a lower frequency. (Compton Effect)
4. The energy from a photon can lead to the creation of matter. The energy of the photon can lead to the production of an electron positron pair. (Pair production)

Of the above, lets first look at Compton scattering. Here, light hits a stationary electron, losing some energy and is scattered. The energy that is lost is given to the electron. After scattering, the frequency of light decreases, and the wavelength increases. The wavelength can be calculated using the following.

$$\lambda' = \lambda + \frac{h}{m_e c}(1 - \cos\phi)$$



Wave Nature of Matter

We know that light behaves as a particle and a wave. But what about matter itself? Does it display the same duality? As it turns out matter also has a wave nature, which was shown by various experiments. The wave nature of matter has a similar behavior to the wave nature of light. The wavelength of matter waves can be calculated using

$$\lambda = h / p$$

This wavelength is referred to as the de Broglie wavelength of a particle.

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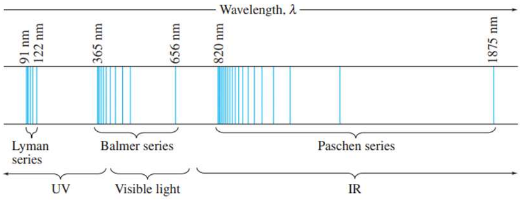
Atomic Spectra and the Bohr Model for the Hydrogen Atom



Since matter has a wave nature, the emitted light that comes from excited atoms when analyzed using the slits of a spectrometer form an emission spectrum, which acts as a method of fingerprinting for identifying gases. Here, we will only be talking about the hydrogen atom, which has the simplest spectrum. The series of spectrum lines formed happen in particular series, depending on the type of electromagnetic wave emitted. These groups are the Lyman, Balmer and Paschen series. The wavelength for the emitted lines obeys the following

$$\frac{1}{\lambda} = R\left(\frac{1}{n'^2} - \frac{1}{n^2}\right)$$

$n' = 1$ for the Lyman series,
$n' = 2$ for the Balmer series,
$n' = 3$ for the Paschen series,

Where n' for the series in consideration and the values of n start at n' + 1 and go to infinity.

Based on the wave nature behavior and the work of Einstein and Plank, Bohr proposed a new model for the atom. He postulated that electrons orbits the nucleus at certain allowed circular paths which would have definite energy levels. The electrons would radiate energy whenever the jump from a higher energy state to a lower energy state. The energy level of the electron is dependent on the orbital they are present in. The orbital is indicated by the principle quantum number n, which you may remember from chemistry. The energy of the electron in a hydrogen atom can be calculated using the following equation

$$E_n = \frac{-13.6\text{ eV}}{n^2}$$

For hydrogen

$$E_n = -(13.6\text{ eV})\frac{Z^2}{n^2}$$

For any atom (Z is the atomic number)

The lowest energy level, n=1, is referred to as the ground state. All the states n > 1 are referred to as the excited states. The energy it takes to remove an electron from atom initially in the ground state is the binding energy. All of the above rules only apply to the hydrogen atom!!!

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CHECK YOUR LEARNING

1. A spaceship passes you at the speed of 0.95c. You measure its length to be 30 m. how long would it be when it is at rest?
2. At what speed will an object's kinetic energy be 10% of its rest energy?
3. What minimum frequency of light is needed to eject electrons from a metal whose work functions is 3×10^{-17} J?
4. A high frequency photon is scattered off of an electron and experiences a change of wavelength of 3×10^{-4} nm. At what angle must a detector be placed to detect the scattered photon?
5. How much total kinetic energy will and electron -positron pair have if produced by a 2 MeV photon?
6. How much energy is needed to ionize a hydrogen atom in the n = 2 state?

THINGS YOU MAY STRUGGLE WITH

1. Time dilation and length contraction can be confusing. Remember that time for a object moving in reference to a observer run slower than when the clock is at rest. The effect of time dilation becomes more noticeable when the velocities are closer to the speed of light. So time expands while the length of objects in motion is shorter than when they are at rest,
2. Relativistic momentum is another confusing concept. With relativity in play, we cannot consider momentum as we do classically and we must account for the everything in relation to the speed of light. The same goes for energy. When we consider relativity, we see that mass and energy are interchangeable. So remember to use these equations that consider relativity here.
3. Velocities of moving objects is no longer considered like we saw in kinematics. You must now use the relativistic addition of velocities to determine the velocity of the moving object relative to your observer. Be careful, what matters most is determining which reference from you are in.
4. Quantization of energy means that energy can only increase or decrease by intervals. For light, each energy quanta are dependent on the FREQUENCY of the light wave.
5. Remember that all the content discussed about the Bohr atom model only applies in reference to the hydrogen atom.

Thanks for checking out these weekly resources! Don't forget to check out our website for group tutoring times, video tutorials and lots of other resource: www.baylor.edu/tutoring ! Answers to check you learning questions are below!

Answers: 1) 96.09m 2) 0.01c 3) 4.53×10^{16} Hz 4) 28.81° 5) 0.978 MeV 6) 3.4 eV

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