GUIDED NOTES

Unit 16: Atomic and Nuclear Physics

OBJECTIVES:

Big Idea 1: Objects and systems have properties such as mass and charge. Systems may have internal structure.
Enduring Understanding 1.A: The internal structure of a system determines many properties of the system.

Essential Knowledge 1.A.2: Fundamental particles have no internal structure.

a. Electrons, neutrinos, photons, and quarks are examples of fundamental particles.

b. Neutrons and protons are composed of quarks.

c. All quarks have electric charges, which are fractions of the elementary charge of the electron. Students will not be expected to know specifics of quark charge or quark composition of nucleons.

Learning Objective 1.A.2.1: The student is able to construct representations of the differences between a fundamental particle and a system composed of fundamental particles and to relate this to the properties and scales of the systems being investigated.

Essential Knowledge 1.A.3: Nuclei have internal structures that determine their properties.

a. The number of protons identifies the element.

b. The number of neutrons together with the number of protons identifies the isotope.

c. There are different types of radioactive emissions from the nucleus.

d. The rate of decay of any radioactive isotope is specified by its half-life.

Essential Knowledge 1.A.4: Atoms have internal structures that determine their properties.

a. The number of protons in the nucleus determines the number of electrons in a neutral atom.

b. The number and arrangements of electrons cause elements to have different properties.

c. The Bohr model based on classical foundations was the historical representation of the atom that led to the description of the hydrogen atom in terms of discrete energy states (represented in energy diagrams by discrete energy levels).

d. Discrete energy state transitions lead to spectra.

Learning Objective 1.A.4.1: The student is able to construct representations of the energy-level structure of an electron in an atom and to relate this to the properties and scales of the systems being investigated.

Enduring Understanding 1.C: Objects and systems have properties of inertial mass and gravitational mass that are experimentally verified to be the same and that satisfy conservation principles.

Essential Knowledge 1.C.4: In certain processes, mass can be converted to energy and energy can be converted to mass according to $E = mc^2$, the equation derived from the theory of special relativity.

Learning Objective 1.C.4.1: The student is able to articulate the reasons that the theory of conservation of mass was replaced by the theory of conservation of mass-energy.

GUIDED NOTES

Enduring Understanding 1.D: Classical mechanics cannot describe all properties of objects.

Essential Knowledge 1.D.1: Objects classically thought of as particles can exhibit properties of waves.

a. This wavelike behavior of particles has been observed, e.g., in a double-slit experiment using elementary particles.

b. The classical models of objects do not describe their wave nature. These models break down when observing objects in small dimensions.

Learning Objective 1.D.1.1: The student is able to explain why classical mechanics cannot describe all properties of objects by articulating the reasons that classical mechanics must be refined and an alternative explanation developed when classical particles display wave properties.

Essential Knowledge 1.D.2: Certain phenomena classically thought of as waves can exhibit properties of particles.

a. The classical models of waves do not describe the nature of a photon.

b. Momentum and energy of a photon can be related to its frequency and wavelength.

Essential Knowledge 1.D.3: Properties of space and time cannot always be treated as absolute.

a. Relativistic mass-energy equivalence is a reconceptualization of matter and energy as two manifestations of the same underlying entity, fully interconvertible, thereby rendering invalid the classically separate laws of conservation of mass and conservation of energy. Students will not be expected to know apparent mass or rest mass.

b. Measurements of length and time depend on speed. (Qualitative treatment only.)

Learning Objective 1.D.3.1: The student is able to articulate the reasons that classical mechanics must be replaced by special relativity to describe the experimental results and theoretical predictions that show that the properties of space and time are not absolute. [Students will be expected to recognize situations in which nonrelativistic classical physics breaks down and to explain how relativity addresses that breakdown, but students will not be expected to know in which of two reference frames a given series of events corresponds to a greater or lesser time interval, or a greater or lesser spatial distance; they will just need to know that observers in the two reference frames can "disagree" about some time and distance intervals.]

Big Idea 4: Interactions between systems can result in changes in those systems.

Enduring Understanding 4.C: Interactions with other objects or systems can change the total energy of a system.

Essential Knowledge 4.C.4: Mass can be converted into energy, and energy can be converted into mass.

a. Mass and energy are interrelated by $E = mc^2$.

b. Significant amounts of energy can be released in nuclear processes.

Learning Objective 4.C.4.1: The student is able to apply mathematical routines to describe the relationship between mass and energy and apply this concept across domains of scale.

GUIDED NOTES

Big Idea 5: Changes that occur as a result of interactions are constrained by conservation laws.
Enduring Understanding 5.B: The energy of a system is conserved.

Essential Knowledge 5.B.8: Energy transfer occurs when photons are absorbed or emitted, for example, by atoms or nuclei.

a. Transitions between two given energy states of an atom correspond to the absorption or emission of a photon of a given frequency (and hence, a given wavelength).

b. An emission spectrum can be used to determine the elements in a source of light.

Learning Objective 5.B.8.1: The student is able to describe emission or absorption spectra associated with electronic or nuclear transitions as transitions between allowed energy states of the atom in terms of the principle of energy conservation, including characterization of the frequency of radiation emitted or absorbed.

Essential Knowledge 5.B.11: Beyond the classical approximation, mass is actually part of the internal energy of an object or system with $E = mc^2$.

a. $E = mc^2$ can be used to calculate the mass equivalent for a given amount of energy transfer or an energy equivalent for a given amount of mass change (e.g., fission and fusion reactions).

Learning Objective 5.B.11.1: The student is able to apply conservation of mass and conservation of energy concepts to a natural phenomenon and use the equation $E = mc^2$ to make a related calculation.

Enduring Understanding 5.C: The electric charge of a system is conserved.

Essential Knowledge 5.C.1: Electric charge is conserved in nuclear and elementary particle reactions, even when elementary particles are produced or destroyed. Examples should include equations representing nuclear decay.

Learning Objective 5.C.1.1: The student is able to analyze electric charge conservation for nuclear and elementary particle reactions and make predictions related to such reactions based upon conservation of charge.

Enduring Understanding 5.G: Nucleon number is conserved.

Essential Knowledge 5.G.1: The possible nuclear reactions are constrained by the law of conservation of nucleon number.

Learning Objective 5.G.1.1: The student is able to apply conservation of nucleon number and conservation of electric charge to make predictions about nuclear reactions and decays such as fission, fusion, alpha decay, beta decay, or gamma decay.

GUIDED NOTES

Big Idea 6: Waves can transfer energy and momentum from one location to another without the permanent transfer of mass and serve as a mathematical model for the description of other phenomena.

Enduring Understanding 6.F: Electromagnetic radiation can be modeled as waves or as fundamental particles.

Essential Knowledge 6.F.3: Photons are individual energy packets of electromagnetic waves, with $E_{photon} = hf$, where h is Planck's constant and f is the frequency of the associated light wave.

a. In the quantum model of electromagnetic radiation, the energy is emitted or absorbed in discrete energy packets called photons. Discrete spectral lines should be included as an example.

b. For the short-wavelength portion of the electromagnetic spectrum, the energy per photon can be observed by direct measurement when electron emissions from matter result from the absorption of radiant energy.

c. Evidence for discrete energy packets is provided by a frequency threshold for electron emission. Above the threshold, maximum kinetic energy of the emitted electrons increases with the frequency and not the intensity of absorbed radiation. The photoelectric effect should be included as an example.

Learning Objective 6.F.3.1: The student is able to support the photon model of radiant energy with evidence provided by the photoelectric effect.

Essential Knowledge 6.F.4: The nature of light requires that different models of light are most appropriate at different scales.

a. The particle-like properties of electromagnetic radiation are more readily observed when the energy transported during the time of the measurement is comparable to E_{photon}.

b. The wavelike properties of electromagnetic radiation are more readily observed when the scale of the objects it interacts with is comparable to or larger than the wavelength of the radiation.

Learning Objective 6.F.4.1: The student is able to select a model of radiant energy that is appropriate to the spatial or temporal scale of an interaction with matter.

Enduring Understanding 6.G: All matter can be modeled as waves or as particles.

Essential Knowledge 6.G.1: Under certain regimes of energy or distance, matter can be modeled as a classical particle.

Learning Objective 6.G.1.1: The student is able to make predictions about using the scale of the problem to determine at what regimes a particle or wave model is more appropriate.

Essential Knowledge 6.G.2: Under certain regimes of energy or distance, matter can be modeled as a wave. The behavior in these regimes is described by quantum mechanics.

a. A wave model of matter is quantified by the de Broglie wavelength that increases as the momentum of the particle decreases.

b. The wave property of matter was experimentally confirmed by the diffraction of electrons in the experiments of Clinton Joseph Davisson, Lester Germer, and George Paget Thomson.

Learning Objective 6.G.2.1: The student is able to articulate the evidence supporting the claim that a wave model of matter is appropriate to explain the diffraction of matter interacting with a crystal, given conditions where a particle of matter has momentum corresponding to a de Broglie wavelength smaller than the separation between adjacent atoms in the crystal.

Learning Objective 6.G.2.2: The student is able to predict the dependence of major features of a diffraction pattern (e.g., spacing between interference maxima) based upon the particle speed and de Broglie wavelength of electrons in an electron beam interacting with a crystal. (de Broglie wavelength need not be given, so students may need to obtain it.)

Big Idea 7: The mathematics of probability can be used to describe the behavior of complex systems and to interpret the behavior of quantum mechanical systems.

Enduring Understanding 7.C: At the quantum scale, matter is described by a wave function, which leads to a probabilistic description of the microscopic world.

Essential Knowledge 7.C.1: The probabilistic description of matter is modeled by a wave function, which can be assigned to an object and used to describe its motion and interactions. The absolute value of the wave function is related to the probability of finding a particle in some spatial region. (Qualitative treatment only, using graphical analysis.)

Learning Objective 7.C.1.1: The student is able to use a graphical wave function representation of a particle to predict qualitatively the probability of finding a particle in a specific spatial region.

Essential Knowledge 7.C.2: The allowed states for an electron in an atom can be calculated from the wave model of an electron.

a. The allowed electron energy states of an atom are modeled as standing waves. Transitions between these levels, due to emission or absorption of photons, are observable as discrete spectral lines.

b. The de Broglie wavelength of an electron can be calculated from its momentum, and a wave representation can be used to model discrete transitions between energy states as transitions between standing waves.

Learning Objective 7.C.2.1: The student is able to use a standing wave model in which an electron orbit circumference is an integer multiple of the de Broglie wavelength to give a qualitative explanation that accounts for the existence of specific allowed energy states of an electron in an atom.

Essential Knowledge 7.C.3: The spontaneous radioactive decay of an individual nucleus is described by probability.

a. In radioactive decay processes, we cannot predict when any one nucleus will undergo a change; we can only predict what happens on the average to a large number of identical nuclei.

b. In radioactive decay, mass and energy are interrelated, and energy is released in nuclear processes as kinetic energy of the products or as electromagnetic energy.

c. The time for half of a given number of radioactive nuclei to decay is called the half-life.

d. Different unstable elements and isotopes have vastly different half-lives, ranging from small fractions of a second to billions of years.

Learning Objective 7.C.3.1: The student is able to predict the number of radioactive nuclei remaining in a sample after a certain period of time, and also predict the missing species (alpha, beta, gamma) in a radioactive decay.

Essential Knowledge 7.C.4: Photon emission and absorption processes are described by probability.
a. An atom in a given energy state may absorb a photon of the right energy and move to a higher energy state (stimulated absorption).
b. An atom in an excited energy state may jump spontaneously to a lower energy state with the emission of a photon (spontaneous emission).
c. Spontaneous transitions to higher energy states have a very low probability but can be stimulated to occur. Spontaneous transitions to lower energy states are highly probable.
d. When a photon of the right energy interacts with an atom in an excited energy state, it may stimulate the atom to make a transition to a lower energy state with the emission of a photon (stimulated emission). In this case, both photons have the same energy and are in phase and moving in the same direction.

Learning Objective 7.C.4.1: The student is able to construct or interpret representations of transitions between atomic energy states involving the emission and absorption of photons. [For questions addressing stimulated emission, students will not be expected to recall the details of the process, such as the fact that the emitted photons have the same frequency and phase as the incident photon; but given a representation of the process, students are expected to make inferences such as figuring out from energy conservation that since the atom loses energy in the process, the emitted photons taken together must carry more energy than the incident photon.]

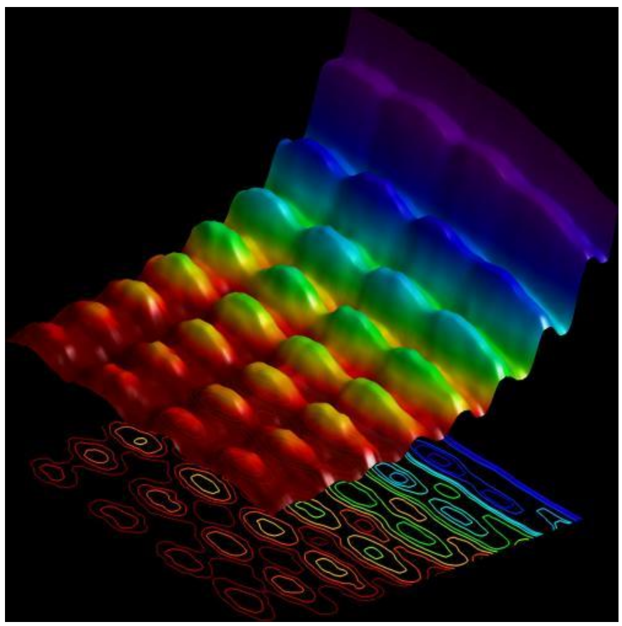
GUIDED NOTES

START HERE…ORGANIZING THOUGHTS

One of the overarching ideas in this unit is whether light (i.e., electromagnetic radiation of any type) is a wave or a particle AND whether matter itself is a wave or a particle. Some assumptions:

1. Objects classically thought of as particles can exhibit properties of waves.
    - Classical mechanics cannot describe all properties of objects. The classical models of objects do not describe their wave nature. These models break down when observing objects in small dimensions.
2. Certain phenomena classically thought of as waves can exhibit properties of particles.
    - The classical models of waves do not describe the nature of a photon.

This issue is complex, and in particular, when looking at the very small scale, "the best we can do is to describe certain results of experiments as analogous to classical particle behavior and others as analogous to classical wavelike behavior while recognizing that the underlying nature of the object has no precise analogy in human-scale experience."[1]



The first ever photograph, published in March, 2015, of light simultaneously showing its wave and particle nature.

[1] From the curriculum guide related to Enduring Understanding 1.D

GUIDED NOTES

NOTES

I. The Nature of Light

A. ____ (Max Plank, 1900, and Albert Einstein, 1905[2])

1. _______________regardless of temperature _____________________________________.

- Very hot objects emit visible light or even higher energy radiation.
- Cooler objects emit visible light weakly or not at all and therefore do not glow.

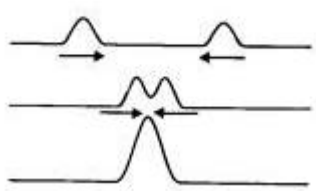
2. ____________ are ____ ______________________________.

3. Plank studied blackbody radiation[3] and determined experimentally that the energy of a particle in any object as it emits radiation can only exist in discrete[4] energy values.

4. Discovery: Einstein realized that these energy values, by the conservation of energy, also equate to the energy emitted. Since the emitted radiation could only exist in the same discrete amounts, he concluded that radiation must be carried by individual "packets" which he named photons. The energy of those emitted photons is found by

where

- _______________is ____
  - He did not know it at the time, but Plank discovered quantum mechanics!
- Be careful: Energy is related to frequency, but classically it is also related to amplitude. The more energy, the larger the amplitude of the vibrating electromagnetic fields. Consider two waves overlapping in superposition, combining their energies. The result is greater amplitude.



Regarding intensity, which is power per area, as amplitude increases, so does intensity. We'll be using these terms a lot.

- Note: Since $c = \lambda f$, $E = {hc}/{\lambda}$. Remembering this could come in handy.

---

[2] 1905 is the same year that Einstein became famous for his special theory of relativity.

[3] Blackbodies reemit all the electromagnetic radiation they absorb.

[4] Discrete means distinct, individual…as opposed to a continuum.

5. Examples:

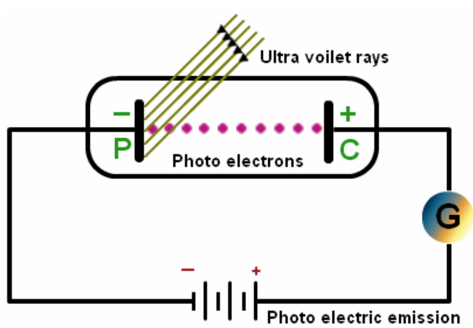
1.) <u>Example 1</u>: Calculate the energy of blue light in joules and electron-volts.[5]

2.) <u>Example 2</u>: Estimate how many photons a 100-W light bulb emits per second in the average visible light spectrum (wavelength about 500 nm.)

B. Proof of the particle model: ____[6]

1. When light shines on a metal surface, electrons are emitted from the surface. One electron is emitted per photon, and the photon ceases to exist. The electrons in this special circumstance are called photoelectrons.

2. A typical photoelectric effect experiment consists of a circuit with a _________________. A photocell consists of a vacuum with a reflective metal surface on one side and an electrode "collector" at the other. When light shines on the metal surface, the circuit connects *despite* the gap inside of the photocell. Why does this prove the photoelectric effect? The light on the metal surface causes the metal surface to send ____________________across the gap to the electrode, connecting the circuit. The photon, meanwhile, ceases to exist. (Photoelectron is just the name given to electrons as they move across the photocell.)



[5] The speed of light, c, is 3.00 x 10^8 m/s.

[6] This was first observed by Heinrich Hertz in 1887. Einstein used this work to prove the existence of photons. Einstein won the 1921 Nobel Prize in Physics for this discovery.

3. The photoelectric effect: Classical wave model or particle model?[7]

The Photoelectric Effect: Predictions from the…	
Classical Wave Model	Particle (Photon) Model
Photoelectron kinetic energy should increase as incident light intensity increases because the amplitude of the electromagnetic field increases with intensity.	Photoelectron kinetic energy should not be affected by incident light intensity, although intensity should affect the number of photoelectrons emitted.
Photoelectron kinetic energy should not be affected by incident light frequency.	Photoelectron kinetic energy should be affected by incident light frequency. Therefore there should be a threshold frequency below which no more photoelectrons will be emitted.

4. Experiments have proven…

a. The **number of photoelectrons are affected by the intensity** of the incident light.

b. The **maximum kinetic energy of the photoelectrons depends on the frequency** of the incident light and not on the intensity.

1.) An electron is held in the metal by attractive forces. Some of the photon's energy must do work to release the electron. This work is called the _________________, ______, and is usually around a few eV[8]. The rest of the photon's energy becomes kinetic energy according to the formula:

If the incident light has enough energy to overcome the work function, then photons are emitted.

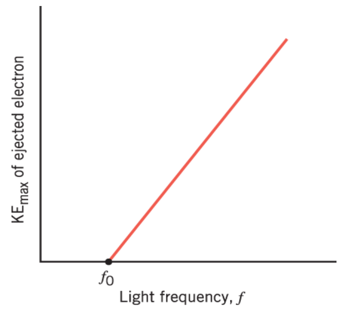
2.) Additionally, what is not on the formula sheet but can be derived:

---

[7] <u>Learning Objective 6.F.3.1</u>: The student is able to support the photon model of radiant energy with evidence provided by the photoelectric effect.

[8] Review: An electron volt is the energy required to move an electron through a potential difference of 1 V.

3.) Note in the original equation, _____ is the ________ and _____ is the ____________ of the following graph showing the K_{max} as a function of frequency for a particular metal. (Other metals would result in other lines parallel to this one.)



4.) Examples:

- Example 3: What is the maximum kinetic energy and speed of an electron ejected from a sodium surface whose work function is 2.28 eV when illuminated by light of wavelength 410 nm.

- Example 4: When light of 200 nm strikes a surface, photons are emitted with a maximum kinetic energy of 1.11 eV. What is the lowest frequency light that can emit photoelectrons from this surface?

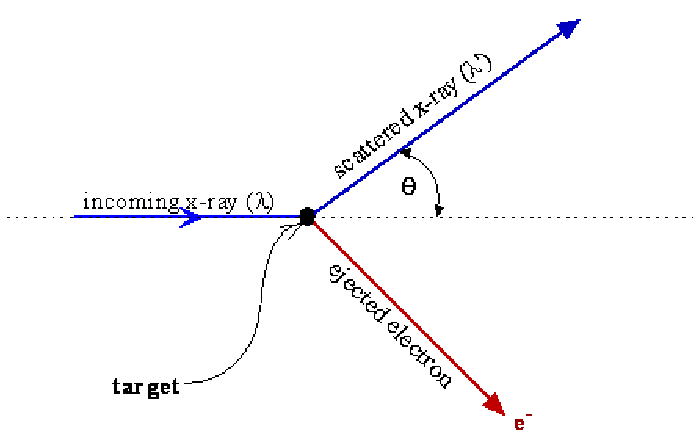
5.) There is a threshold frequency below which no more photoelectrons will be emitted

- Example 5: In a photoelectric effect experiment, there is no current below 600 nm. (a) What is the work function for this metal? (b) What is the threshold frequency? (c) Sketch a graph of K_{max} as a function of frequency. (d) What should the slope of this graph equal?

C. More proof of the photon model: _______________________________

1. The photon nature of light proposed by Einstein in 1905 didn't fully gain hold until the work of Arthur Compton (1892 – 1962) who in 1923 discovered what is now called the Compton effect.

2. Compton's experiment: Compton collided x-rays against materials with loosely-bound electrons (such as the conductor graphite.) When the collisions occurred, electrons were ejected while some of the incident x-ray radiation glanced off (was "scattered.") ____________________ ____. This could only occur if light consisted of ________________that _______________________________________ ___________________________________. Calculations of the conservation of energy matched the predictions based on E_{photon}.



Compton also examined these collisions from the perspective of the conservation of momentum. He determined that ____, and he found the momentum of a photon is related to its wavelength by

Remember…

<u>Big Idea 6</u>: Waves can transfer energy and momentum from one location to another without the permanent transfer of mass and serve as a mathematical model for the description of other phenomena.

<u>Homework 1</u>: Chapter 29 Conceptual Questions 3, 5, 6, 7, 9, and Problems 1, 3, 13, and 14

GUIDED NOTES

II. Atomic Energy Levels & Absorption/Emission of Light by Atoms

A. Introduction - The Bohr model: In 1913 Neils Bohr (1885-1962) determined that ______________ ____ with specific quantities of energy, and ____ ____.

Therefore the _________________________________ of light _________________________________ ________________ could be predicted.

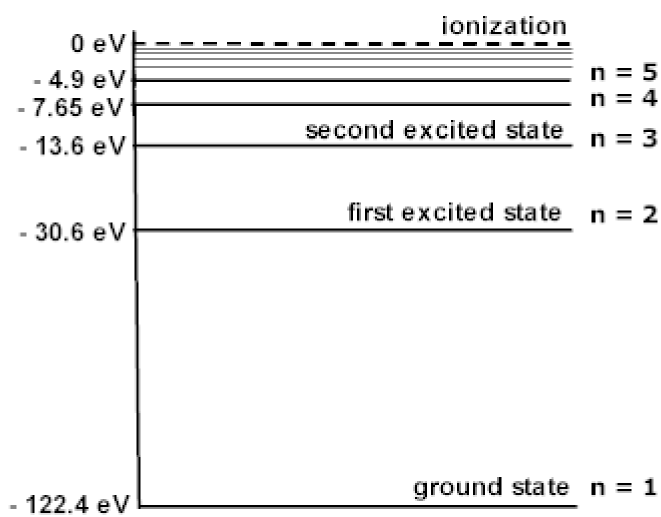
B. _________________________________ (a.k.a. _________________________________) are orbits electrons can occupy _________________________________. These exist ______________________ _________________________________.

1.) _________________________________: The _________________________________level for an electron to orbit; _________________________________.

2.) _________________________________: Any energy level higher than the ground state.

3.) Energy approaches zero as the radius approaches infinity. When the energy reaches zero, the atom loses the electron and becomes ________________. This takes an input of energy.

- Energy is measured relative to the zero ionization level. Therefore all bound electrons have negative energy (similar to negative potential energy.) Therefore it takes energy equal to ΔE to move the electrons up a level.



- Note, then that it takes MORE energy to remove a low-level, ground state electron from the atom than it does to remove an electron whose energy is actually closer to 0 eV because ΔE is greater for the ground state electron. This is why it is easier to lose outer electrons than electrons close to the nucleus. In terms of energy, we consider this to be an “energy well.”

C. Absorption and emission of light by atoms helped prove Bohr's model.

1. Assumptions: Photon emission and absorption processes are described by _______________.

a. _________________________________: An atom in a given energy state may absorb a photon of the right energy and move to a higher (more excited) energy state.[9]

b. _________________________________: An atom in an excited energy state may jump spontaneously to a lower energy state with the emission of a photon.

c. *Spontaneous transitions to higher energy states have a very low probability but can be stimulated to occur (stimulated absorption.) Spontaneous transitions to lower energy states are highly probable (spontaneous emission.)*

d. _________________________________: When a photon of the right energy interacts with an atom in an excited energy state, it may stimulate the atom to make a transition to a lower energy state sooner than it would spontaneously. The original photon is still present, plus an _________________________________is emitted (just as in spontaneous emission.)

- The two photons will have the _________________________________and will be ________________ with each other. This creates ________________________________ and is how ___________ work ("light amplification by stimulated emission of radiation")
- Since the atom loses energy in the process, the emitted photons taken together must carry more energy than the incident photon.

2. _________________________________: Because the orbits are quantized, photons can only be absorbed or emitted in quanta equal to the change in energy when an electron moves from one orbit to another orbit. Therefore the frequencies of incident or emitted light can be calculated.

a. <u>Example 6</u>: Previously we saw an energy-level diagram for a particular atom. (a) How much energy is required to move the electron from the ground state to the first excited state? (b) What will be the energy of the photon emitted when that electron returns to the ground state? (c) What will be the frequency and wavelength of that photon? (d) What is the ionization energy of that electron?

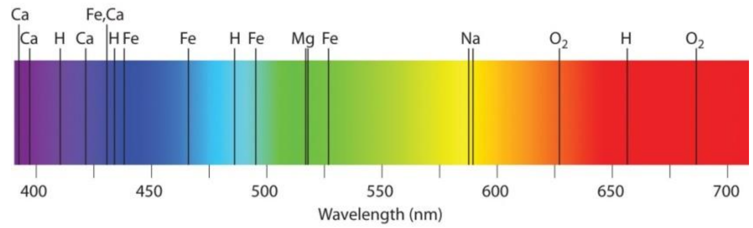
---

[9] The "right energy" means that the photon's energy equals the difference between two energy levels of an electron in that atom. See #2.

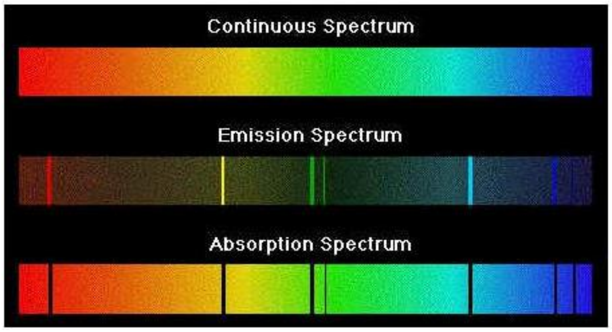
b. ________________of gases

1.) Each element has different stationary states. Therefore each element absorbs or emits a unique spectrum of radiation.

2.) ________________________________: When an element is exposed to radiation, a unique spectrum emerges containing gaps, or bands, where photons were absorbed.



3.) ________________________________: Gases can also be excited to emit radiation via heating or exposure to a potential difference (voltage.) Gas of each element emits a unique "emission spectrum" of only the wavelengths absorbed in their absorption spectrum.



Homework 2: Chapter 30 Conceptual Question 3 and Problems 7 and 12 (Refer to Figure 30.9.)

GUIDED NOTES

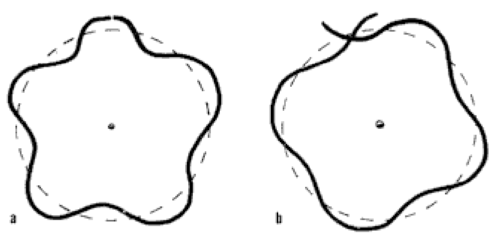
III. The Wave-Particle Duality

A. _________________________________

1. In 1923 Louis de Broglie[10] hypothesized that if light behaves as both a wave and a particle, then perhaps ____.
He extended Compton's formula for the momentum of photons to all matter to show that the ____.
The wavelength is called _________________________________.

(This is the ___________________________we've seen before _________________________________.)

2. The deBroglie wavelength explains stationary states of electrons. Bohr knew electrons orbited in quantum levels but didn't know why. De Broglie's work showed that the reason for the quantum orbits is that electrons, previously thought to be particles, are also waves that orbit such that they form circular standing waves. Therefore, since the electrons can't interfere with themselves, only orbital radii that allow closed standing waves can exist. This means that electrons, which can behave as particles under some circumstances, also behave as waves. De Broglie therefore proposed that if electrons act both as particles and waves, so must all matter.



Yes No

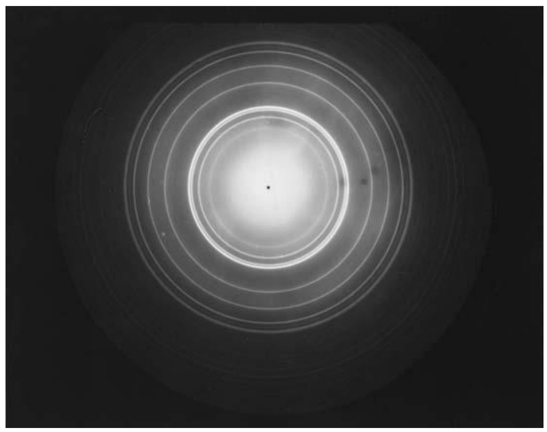
a. The _________________________________is _________________________________ of the de Broglie wavelength.

b. Transitions between stationary orbits due to emission or absorption of photons can be modeled as transitions between standing waves.

[10] Dude was a French duke!

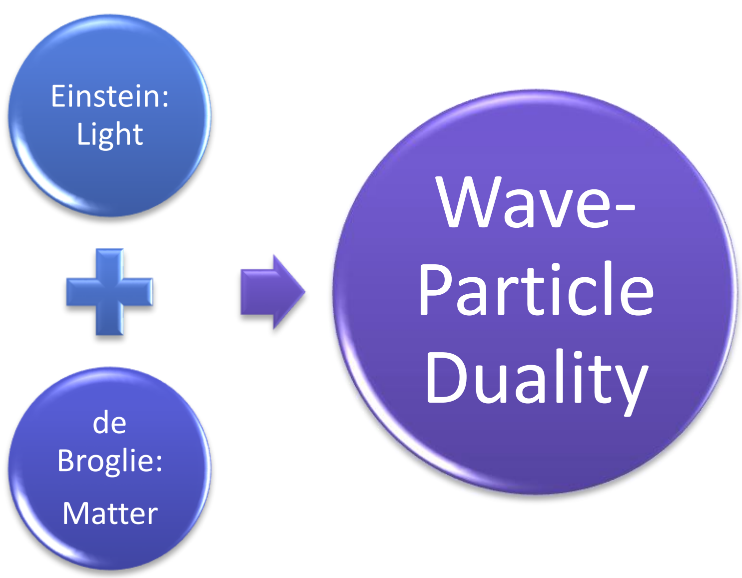
3. The 1927 __________________________________provided evidence for this wave nature of electrons.

- Hypothesis: If the _____________ can really behave as a wave, it ___________________.
- Method: Davisson and Germer ____ __________________________________ and ______________________________________. This confirmed the de Broglie wavelength of matter.
- In the same year, G.P. Thomson also conducted a similar experiment with similar results, helping to make the wave nature of matter conclusive.



The electron diffraction pattern of a beryllium atom.

- Later experiments showed protons and neutrons behave as waves, as well. We continue to "upsize," trying to prove larger and larger objects act as waves.



- Example 7: Explain narratively how you could determine the major features of a diffraction pattern (e.g., spacing between interference maxima) based upon the particle speed and de Broglie wavelength of electrons in an electron beam interacting with a crystal if you're not given the de Broglie wavelength of the electrons? (*If we have not gotten to diffraction patterns, we will just do this example together in class.*)

B. If everything is a particle AND a wave, which model do we choose? Answer: ______________________________ is more appropriate ____________________________________ of the problem.

1. *Electromagnetic radiation can be modeled as waves or particles. Which model is more appropriate depends on both the spatial and temporal scale of the problem.*
   - *The particle-like properties of electromagnetic radiation are more readily observed when the energy transported during the time of the measurement is comparable to* E_{photon}.
   - *The wavelike properties of electromagnetic radiation are more readily observed when the scale of the objects it interacts with is comparable to or larger than the wavelength of the radiation.*
2. *Matter can be modeled as waves or particles. Which model is more appropriate depends on the spatial scale of the problem.*
   - *If the wavelength is very small relative to the scale of its frame of reference, matter acts like matter.*
   - *If the wavelength is very large relative to the scale of its frame of reference, matter acts like a wave.*
3. Examples:
   - Example 8: A 5kg bicycle moves at 2m/s. What's its wavelength? Does it look like matter or a wave?

- Example 9: What is the de Broglie wavelength of an electron with a speed of 2.2E6m/s, which is the average speed of a ground state electron in hydrogen? Within the hydrogen atom (radius 0.05 nm) does it act like a particle or wave? What does it act like from our point of view?

C. The ________________________________

1. de Broglie gave us the wavelength of matter. Erwin Schrödinger's wave function[11] equation ____.

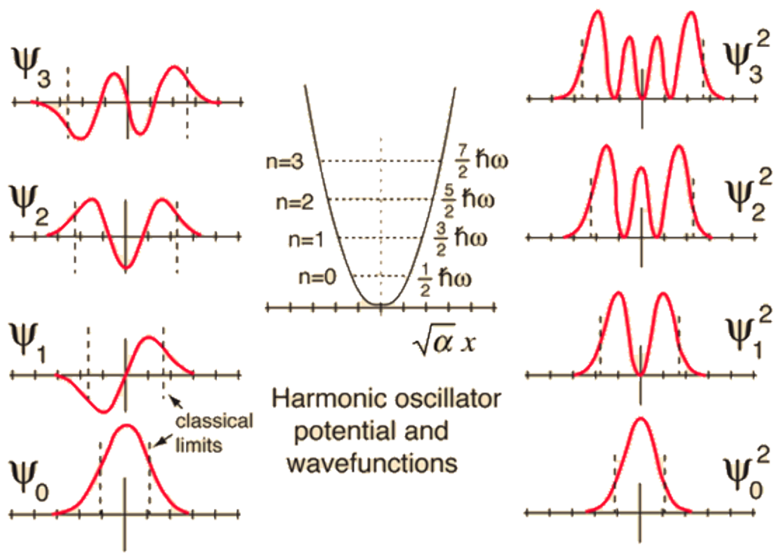
2. Classical mechanics vs quantum mechanics:

   a. Classical mechanics: We can determine the location and behavior of mass using Newtonian mechanics. This is fine if we consider a scale where matter behaves as matter.

   b. Quantum mechanics: When the scale requires us to consider matter as a wave, we must use probabilistic tools.

   - If matter, such as an electron, behaves as a wave, we cannot locate it (as a particle) exactly and can only consider the likelihood, or probability, that it will be at a particular location at a particular time.
   - Schrödinger's wave function equation, when graphed, uses a value called the wave function, Ψ, to show us the ________________________________of a matter wave, which, therefore, helps us determine the most probable location of the particle. Graphs of Ψ^2 vs position show us the most probable location of a particle exist where the "probability amplitude" is largest on the graph.

[11] The wave function uses Calculus, so you're not responsible for it quantitatively.



These are graphs of Ψ vs. x (left) and Ψ^2 v. x (right) for electrons at various stationary states in a particular atom. Usually the Ψ^2 v. x graph is used. Where the graph amplitude is highest, the probability is highest to locate the electron at that position.

Homework 3: Chapter 29 Conceptual Questions 11, 12 and Problems 21, 22, 24

GUIDED NOTES

IV. Nuclear Physics

A. ________________________________are the building blocks of all matter.

1. Fundamental particles have ____.

2. Electrons, neutrinos, photons, leptons, and quarks are examples of fundamental particles.

3. ________________________________ are ________________________________and are, therefore, ______ fundamental particles.

4. ________________ (but not *all* fundamental particles) ________________________________, which are ____of the electron.

B. Nuclei have internal structures that determine their properties.

1. The number of protons identifies the element.

2. The number of protons in the nucleus determines the number of electrons in a neutral atom, and the number and arrangements of electrons cause elements to have different properties.

3. Structure of the nucleus

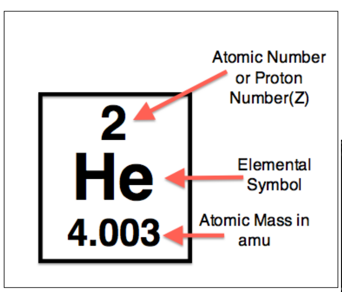
a. The vast majority of an atom's mass exists in its nucleus.

1.) __________________________: The number of protons (Z)

2.) ________________________________: The number (A) of protons and neutrons

b. ________________: Mass number can change when the number of neutrons changes.

- Atoms of the same atomic number but different mass numbers are isotopes of the same element.



c. Strong nuclear force: The strongest force in the universe; strong enough to overcome nuclear repulsion based on the electric force between the protons; very, very small range such that protons farther than about 10^{-15} m apart become overcome by electric repulsions and do not stay together.

GUIDED NOTES

C. Nuclear reactions

1. All nuclear reactions obey the laws of physics:

a.) Law of conservation of charge

b.) ____: The total number of nucleons is conserved.

c.) ____,

____

____

(See energy-mass equivalence, $E = mc^2$, below.)

2. ________________________________ (a.k.a. radioactivity) reactions occur when an unstable, radioactive nucleus undergoes a change in its atomic number, mass number, or both.

a. ______________

1.) ____________________are 2e positively charged helium nucleii, ________

(Remember e is the positive fundamental charge.)

2.) Therefore ____ such that:

3.) Example 10: Uranium (A = 238 and Z = 92) undergoes alpha decay to create Thorium (Z = 90.) (a) Sketch the reaction and (b) Narratively explain how the laws of physics govern this reaction.

b. _______________

1.) ________ particles are _______________, and ________ particles are _______________ (same properties as electrons but with a positive charge.) (These can be written $\frac{0}{-1}e$ and $\frac{0}{1}e$.)

2.) _______________ can ____.
When this happens, a ________ particle is emitted and the decay reaction results in a ______________________________ with ______________________________:[12]

3.) _______________ can ____.
When this happens, a ________ particle is emitted and the decay reaction results in a ______________________________ with ______________________________:

4.) Examples:

a.) Example 11: Draw the reaction when thorium (A = 234 and Z = 90) becomes protactinium (A = 234 and Z = 91.) Narratively explain how the laws of physics govern this reaction.

b.) Example 12: Draw the reaction for the beta decay of $\frac{19}{10}Ne$ to $\frac{19}{9}F$. Narratively explain how the laws of physics govern this reaction.

---

[12] $\overline{v}$ is an antineutrino, a charge-less, almost mass-less particle that accounts for a slight reduction in system energy during the decay process. v is a neutrino. They are a matter/anti-matter pair. Its mass is 0.0006% of an electron's mass.

c. ________________

1.) _________ can be ______________________ (similar to the excited states of electrons) when they have undergone collisions or when they have just been formed by another decay process. When they reduce to a lower energy state, they emit a high energy photon whose wavelength can be determined as usual.

2.) The process:

where the asterisk designates the high energy state of the parent.

3.) Example 13: $\frac{12}{5}B$ undergoes Beta decay to become $\frac{12}{6}C$ in an excited state before releasing a gamma ray and becoming stable. The entire reaction reduced the nucleus' energy by 13.4 MeV, but the beta particle only carried away 9.0 MeV. Draw the entire process and determine the wavelength of the released photon.

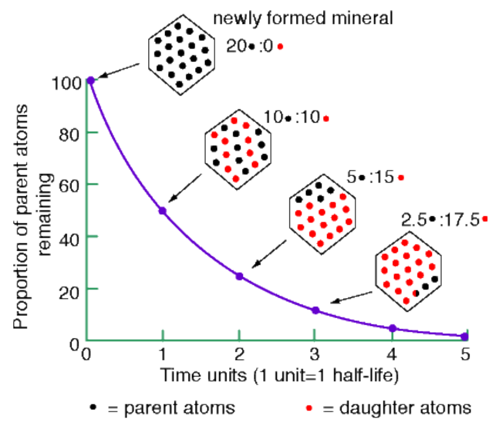
d. _______________ and __________________ in nuclear reactions: The spontaneous radioactive decay of an individual nucleus is described by probability.

1. In radioactive decay processes, we cannot predict when any one nucleus will undergo a change; we can only predict what happens on the average to a large number of identical nuclei. The half-life concept does this for us.

2. _______________: The time for half of a given number of radioactive nuclei to decay is called the half-life.

a. Different unstable elements and isotopes have vastly different half-lives, ranging from small fractions of a second to billions of years.

b. Graphical analysis:



c. Barely-quantitative example: Scientists who study fossils use carbon dating to determine the age of a specimen. Living organisms have a certain amount of a radioactive isotope of carbon, ${}^{14}_{6}C$ that has a half-life of 5730 years. This isotope undergoes radioactive decay to form ${}^{14}_{7}N$ isotope. (a) How old is a fossil whose original ${}^{14}_{6}C$ has reduced to 25% of its original content? (b) What is the probability that any individual ${}^{14}_{6}C$ atom has decayed during this time? (c) Describe the radioactive decay process involved and relate it to the conservation of mass and the conservation of energy.

3. ______________________________

a. In nuclear fission a massive atomic ______________________________ into two smaller nuclei. The resulting particles are released with high amounts of kinetic energy (measuring in the MeV range!)

b. ____ occurs when a parent nucleus is bombarded by a slow-moving neutron that nestles into the parent nucleus. This destabilizes the parent nucleus, and fission begins.

1.) When this happens, neutrons are also released. These released neutrons can initiate more fission reactions, setting off a ______________________________ ______________________________.

2.) For example: One neutron induces uranium to split into Xenon, Strontium and two neutrons.

Homework 4: Chapter 31 Conceptual Questions 1, 2, 3, 9, and 11 (and look at what page you're on!) and Problems 17, 18, 19, 21

GUIDED NOTES

V. Einstein's Special Theory of Relativity and Mass-Energy Equivalence (1905)

A. Review: Reference frames and classical mechanics (a.k.a., "Don't freak out…You already understand relativity.")

1. In ______________________________, the ____.

- For example: If you are riding in a car that is moving at a constant velocity, and you drop a French fry, it obeys the laws of physics, appearing to free fall straight down from your hand into your lap. The car is an inertial reference frame with regard to the French fry because the laws of motion applied to the fry. However, to someone watching you drive by as you dropped the French fry, the fry would appear to move as a projectile. Again the fry obeys the laws of motion, so this is also an inertial reference frame. This is Galilean-Newtonian relativity…The motion of the fry is different *relative* to different reference frames, but in all reference frames, the laws of motion apply. In other words, neither the car's nor the bystander's reference frame was a special exception to the rules.

2. **Classical mechanics describes the motion of objects when their SIZE is the same in different reference frames AND they experience time at the same rate in different reference frames. In such cases, Newtonian physics works.**

B. ______________________________

1. Experimental background: (For reference only….You are not responsible for this part.)

a. In the late 1800s J.C. Maxwell discovered that the speed of light in a vacuum is $c = 3.0\text{E}8$ m/s. The question arose: In what reference frame does light have this speed? Maxwell's equations did not allow for light to have different speeds in different reference frames, so the question arose: Is there a particular absolute reference frame in which light has this speed?

b. In 1887 in Cleveland at what is now Case Western Reserve University in the basement of a building that has since been demolished (ugh!), A.A. Michelson and E.W. Morley devised an experiment that showed that the speed of light in air is *not* different in different inertial reference frames. In other words, regardless of the perspective from which light is observed, the speed of light is always the same. [13] This suggested to Einstein that light must be viewed differently with regard to reference frame.

[13] This is in regard to the speed of light in a vacuum and does not refer to the fact that light slows down in different materials, à la refraction.

c. In 1905 Einstein published two papers that made him famous, *On the Electrodynamics of Moving Bodies* and *Does the Inertia of a Body Depend on Its Energy Content?*[14] In these papers he examined light and outlined his special theory of relativity and explained the energy-mass equivalence, $E = mc^2$.

2. ____:

a. The ____

____

and there is ____

than any other. No single reference frame can be thought of stationary, so all reference frames must be considered relative to all other reference frames.

- If you're driving north, doesn't the world appear to you to be moving south?

b. ____

____.[15]

This means that light itself is its own reference frame, and two observers traveling at different speeds relative to a ray of light will experience the light ray to have the same speed. This conflicts with our prior concepts of the observer as defining the reference frame.

3. Special relativity leads us to unique conclusions, including time dilation and length contraction.

a. _____________________________: Time is not absolute. The _______________something moves relative to an observer in a different reference frame, the _______________time will travel relative to that reference frame.

b. Examples:

- ____. Observers at different distances from the events will observe them to have occurred at different times relative to each other based on the distance between the event and the observer. This is because light will take different amounts of time to reach each observer. Therefore *time itself is not absolute* and passes differently in different reference frames. The faster an event moves relative to an observer, the longer the event will appear to take.

[14] He became so famous so fast that people called 1905 Einstein's miracle year!

[15] As a counter-example, consider the Doppler effect of other waves.

- Synchronized clocks held by two observers who are traveling at different speeds (relative to the speed of light) will run at different rates. The faster the observer holding the clock is moving, the slower the clock will appear to run to an observer who is moving slower.

The person wearing this watch is moving close to the speed of light compared to you. This watch appears to you to be incredibly slowly.

You are wearing this watch. This watch is at rest relative to you. It appears to you to be moving at a normal rate.

★Here's the fun part: To the other person, YOUR watch appears to be running slowly. That's relativity!

- Fundamental particles, such as muons, in particle accelerators that make them travel near the speed of light appear to have longer lives than they would if they were at rest relative to the observer.

b. _______________________________: Space itself is also not absolute. The ____________ something moves relative to an observer in a different reference frame, the _____________ it will appear to be relative to that reference frame.[16] This is because ___________________ ____.

[16] Note that length contraction occurs in the direction of travel, so it is only a length contraction and not a length-height-width contraction.

C. ____

1. After realizing that time and size are relative, Einstein explored the question of whether mass is also relative. Indeed he found out that it increases as an object moves faster relative to another object according to the following formula:

$$m = \frac{m_0}{\sqrt{1 - {v^2}/{c^2}}}$$

(You are not responsible for this formula. It is included her to help conceptually.)

____ the _______________ of the object ____. It therefore becomes ____, and the speed of light is said to be the “cosmic speed limit.”

b. Using a special relativistic view of the work-energy theorem, Einstein considered the work required to increase the kinetic energy of an object as it approached the speed of light. In so doing, he realized that mass and energy are equivalent in that a gain/loss of one becomes a loss/gain in the other according to the formula

c. Relationship to ______________________________:

1.) A quick review: All nuclear reactions obey the laws of physics:

a.) Law of conservation of charge

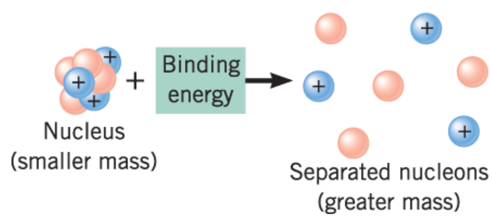
b.) Law of conservation of nucleon number: The total number of nucleons is conserved.

c.) In radioactive decay, mass and energy are interrelated, and energy is released in nuclear processes as kinetic energy of the products or as electromagnetic energy. This energy is related to the energy-mass equivalence.

2.) ______________________________: The nucleons (protons and neutrons) in a nucleus are held together by the strong nuclear force. Therefore it takes a lot of energy to break it apart during fission and decay. This energy is called the ______________________________ . When the binding energy is added to the parent, it ______________________________, making the ____. In other words, the parent has less mass than the products of the fission!

- This is called mass defect, or Δm, and ____________________________________ ______________________________. Alternately, the binding energy (the energy that converts to mass when fission occurs) is equal to mass times c^2 via Einstein's equation:

$$\Delta E = (\Delta m)c^2$$



- Example 1,000,000: The mass of one neutron is 1.6749 E-27kg, and the mass of one proton is 1.6726 E-27 kg. (a) What is the mass defect of an isotope of helium He_2^4 whose mass is 6.6447E-27kg? (b) What is its binding energy? (c) Restate the law of conservation of mass and the law of conservation of energy to explain this phenomenon.

3.) In radioactive decay processes, the daughter nucleus and particles have less mass than the parent. Again, the missing mass is converted to the energy that is released during the decay.

- Example 1,000,0001: Consider the alpha decay of $^{238}_{92}U$…

$$^{238}_{92}U \rightarrow \ ^{234}_{90}Th + \ ^{4}_{2}He$$

The mass of the uranium is 238.0508 atomic mass units (a different unit from kg). The mass of the thorium combined with the alpha particle is 238.0462 atomic mass units, a difference of 0.0046 atomic mass units. The missing mass converts to 4.3 MeV of energy. (a) How much energy is that in Joules? (b) The mass of an alpha particle is 6.64424 E-27kg. What will be the resulting velocity of the alpha particle? (c) Restate the law of conservation of mass and the law of conservation of energy to explain this phenomenon.

Homework 5: Chapter 28 Conceptual Questions 1-6, 12, 13 and Chapter 31 Problem 10 (Refer to page 976 for the masses of neutrons and protons in u.)