Modern Physics

TOPIC 6

How Scientists Study Modern Physics

Are the glass tubes used to make "neon" signs always filled with neon?

Although these bright lights are commonly called neon lights, the tubes can actually contain other gases such as mercury vapor, the noble gases helium, argon, or krypton, or a combination of gases. The gas inside the tube is at low pressure. When a high potential difference is applied to the metal electrodes at each end of the tube, electrons flow through the tube. This excites the gas atoms. When electrons in the excited atoms fall to lower energy levels, the photons that are emitted possess energies that are characteristic of the gas or gases. Viewed through a spectroscope the light would appear as the bright-line spectrum of the gas or gases present in the tube. To the naked eye, the light appears as a characteristic glow.

When viewed, neon appears as reddish orange, mercury vapor as light blue, argon as lavender, and krypton as grayish green. A variety of different colors is produced by coating the inside of the tubing with a phosphor or by using colored tubing.

TOPIC 6

Modern Physics

Vocabulary

absorption spectrum	excited state	quantized
antimatter	ground state	quantum
antiparticle	hadron	quantum theory
antiquark	ionization potential	quark
atom	lepton	spectral line
atomic spectrum	meson	Standard Model of Particle Physics
baryon	neutrino	stationary state
bright-line spectrum	nucleus	strong nuclear force
emission spectrum	photon	universal mass unit
energy level	Planck's constant	
energy-level diagram	positron	

Wave-Particle Duality of Energy and Matter

Light, a form of electromagnetic radiation, can be represented as a wave propagated by an interchange of energy between periodically varying electric and magnetic fields. Waves of electromagnetic energy are identified by their frequency, wavelength, amplitude, and velocity. In addition, electromagnetic radiation exhibits the phenomena of diffraction, interference, and the Doppler effect, which are readily explained by a wave model of light.

Waves Have a Particle Nature

The wave model of light, however, cannot explain other phenomena such as interactions of light with matter. In these interactions, light—or other electromagnetic radiation—acts as if it is composed of particles possessing kinetic energy and momentum. For example, when light strikes matter, some of the light's momentum is transferred to the matter. In the latter part of the nineteenth century it was discovered that light having a frequency above some minimum value and incident on certain metals caused electrons to be emitted from the metal. This phenomenon, called the photoelectric effect, could not be explained by a wave model of light. Albert Einstein explained the phenomenon using quantum theory developed by Max Planck.

Quantum Theory

Quantum theory assumes that electromagnetic energy is emitted from and absorbed by matter in discrete amounts or packets. Each packet of electromagnetic energy emitted or absorbed is called a **quantum** (plural, quanta) of energy. The amount of energy E of each quantum is directly proportional to the frequency f of the electromagnetic radiation. The proportionality constant between the energy of a quantum and its frequency is called **Planck's constant,** h. Thus, the energy of a quantum is given by this formula.

$$E = hf$$

The energy E is in joules, the frequency f is in hertz, and Planck's constant h is a universal constant equal to 6.63×10^{-34} joule · second (J · s). The small energy values of quanta are often expressed in electronvolts, eV (1 eV = 1.60×10^{-19} J).

The quantum, or basic unit, of electromagnetic energy is called a **photon.** Although a photon is a massless particle of light, it carries both energy and momentum. The energy of a photon can be found using the previous equation. For light in a vacuum, $f = c/\lambda$ the energy of a photon can also be described in this way.

$$E_{photon} = hf = \frac{hc}{\lambda}$$ (R)

The equation states that the energy of a photon is directly proportional to its frequency and inversely proportional to its wavelength.

SAMPLE PROBLEM

The energy of a photon is 2.11 electronvolts.

(a) Determine the energy of the photon in joules.
(b) Calculate the frequency of the photon.
(c) Identify the color of light associated with the photon.

SOLUTION: Identify the known and unknown values.

Known	*Unknown*
$E = 2.11$ eV	$E = ?$ J
$h = 6.63 \times 10^{-34}$ J · s	$f = ?$ Hz
1 eV = 1.60×10^{-19} J	color = ?

1. Convert electronvolts to joules using the relationship 1 eV = 1.60×10^{-19} J.

$$2.11 \text{ eV}\left(\frac{1.60 \times 10^{-19} \text{ J}}{1 \text{ eV}}\right) = 3.38 \times 10^{-19} \text{ J}$$

2. Solve the formula $E_{photon} = hf$ for frequency f.

$$f = \frac{E_{photon}}{h}$$

3. Substitute the known values and solve.

$$f = \frac{3.38 \times 10^{-19} \text{ J}}{6.63 \times 10^{-34} \text{ J} \cdot \text{s}} = 5.10 \times 10^{14} \text{ Hz}$$

4. According to the electromagnetic spectrum chart found in the *Reference Tables for Physical Setting/Physics*, a frequency of 5.10×10^{14} Hz corresponds to yellow light.

Photon-Particle Collisions

The photoelectric effect demonstrates that when a photon in the visible light range is incident on a metal surface, the photon's energy is completely absorbed and transferred to the emitted electron. However, when X-ray photons, which have much higher frequencies and energies than photons of visible light, strike a metal surface, not only are electrons ejected but electromagnetic radiation of lower frequency is also given off.

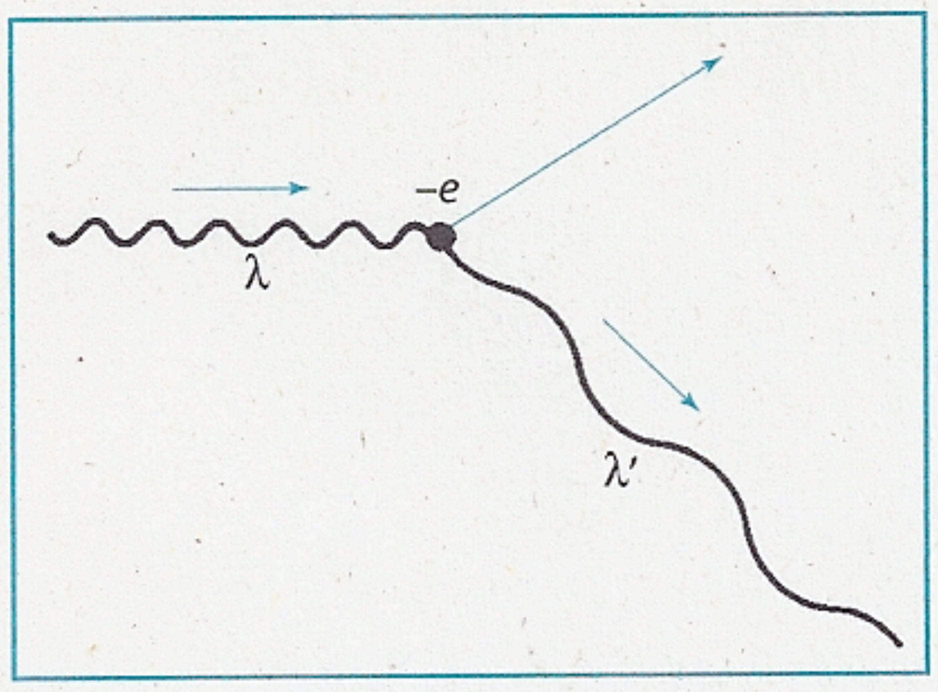


Figure 6-1. A collision of an X-ray photon and an electron in an atom: Besides the electron ejected from the atom, a photon of lower energy (longer wavelength) is also emitted (scattered) by the atom. The energy transferred to the electron equals the difference in energy between the incident photon and the scattered photon. The vector sum of the momentum of the electron and the scattered photon also equals the momentum of the incident photon.

When an X-ray photon and an electron collide, some of the energy of the photon is transferred to the electron and the photon recoils with less energy. Less energy means that the photon has lower frequency. Figure 6-1 illustrates this phenomenon.

Both energy, a scalar quantity, and momentum, a vector quantity, are conserved in this interaction, just as they are in collisions between particles. The incident photon loses energy and momentum, while the electron gains energy and momentum. Photons in a vacuum always travel at the speed of light. Thus, the momentum of a photon depends only on its wavelength or frequency.

Particles Have a Wave Nature

Just as radiation has both wave and particle characteristics, matter in motion has wave as well as particle characteristics. The wavelengths of the waves associated with the motion of ordinary objects, such as a thrown baseball, are too small to be detected. But the waves associated with the motion of particles of atomic or subatomic size, such as electrons, can produce diffraction and interference patterns that can be observed. Diffraction and interference phenomena provide evidence for the wave nature of particles.

Review Questions

1. In which part of the electromagnetic spectrum does a photon have the least energy?
   (1) gamma rays (3) visible light
   (2) microwaves (4) ultraviolet

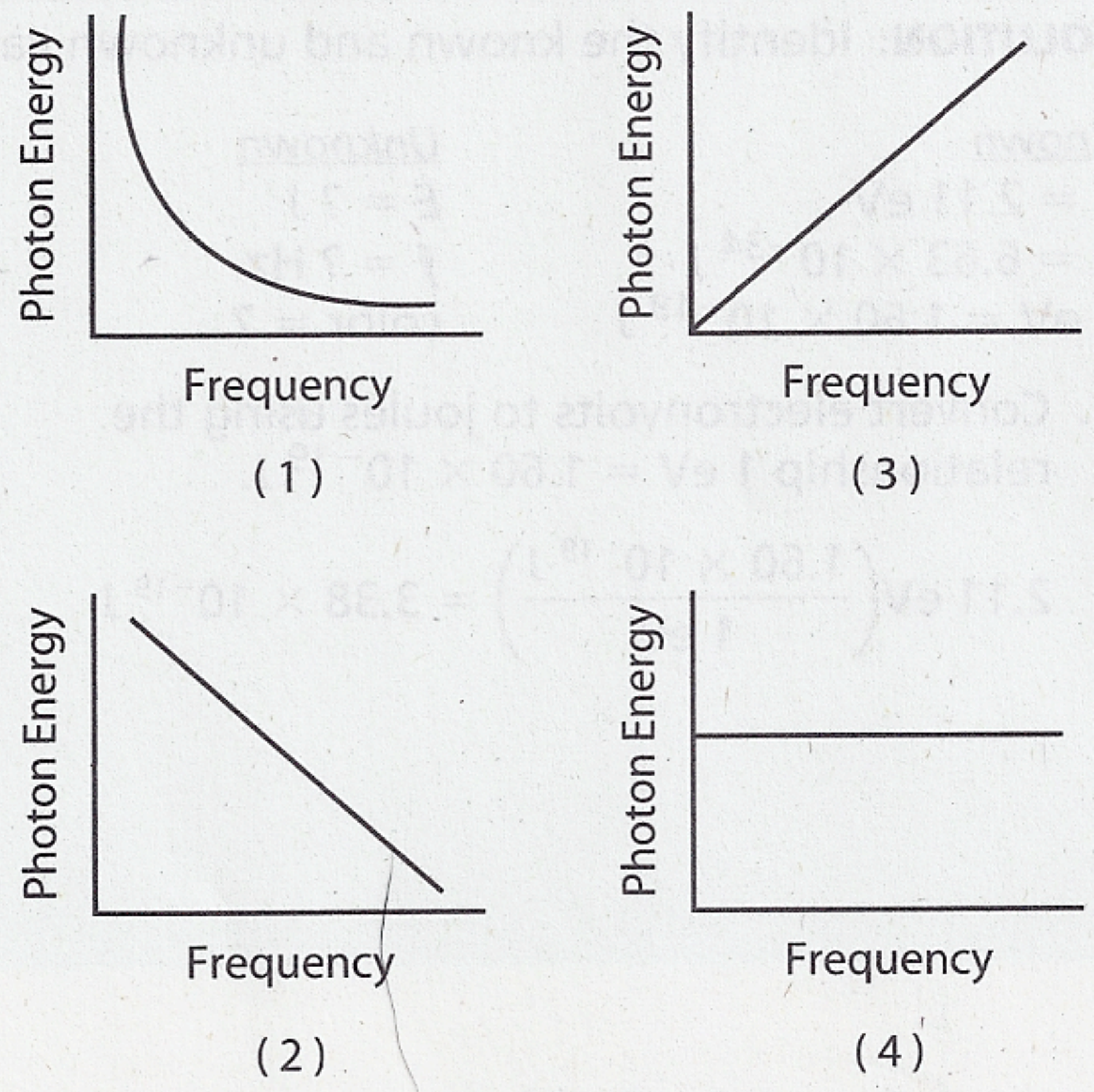
2. The energy of a photon varies inversely with its
   (1) frequency (3) speed
   (2) momentum (4) wavelength

3. Compared to the frequency and wavelength of a photon of red light, a photon of blue light has a
   (1) lower frequency and shorter wavelength
   (2) lower frequency and longer wavelength
   (3) higher frequency and shorter wavelength
   (4) higher frequency and longer wavelength

4. A photon has an energy of 8.0×10^{-19} joule. What is this energy expressed in electronvolts?
   (1) 5.0×10^{-38} eV (3) 8.0×10^{-19} eV
   (2) 1.6×10^{-19} eV (4) 5.0 eV

5. The slope of a graph of photon energy versus photon frequency represents
   (1) Planck's constant
   (2) the mass of a photon
   (3) the speed of light
   (4) the speed of light squared

6. Which graph best represents the relationship between photon energy and photon frequency?



7. A photon of green light has a frequency of 6.0×10^{14} hertz. The energy associated with this photon is
   (1) 1.1×10^{-48} J (3) 5.0×10^{-7} J
   (2) 6.0×10^{-34} J (4) 4.0×10^{-19} J

8. Calculate the energy of a photon having a wavelength of 4.00×10^{-7} meter in air.

9. An X-ray photon collides with an electron in an atom, ejecting the electron and emitting another photon. During the collision there is a conservation of
(1) momentum only
(2) energy only
(3) both momentum and energy
(4) neither momentum nor energy

10. Experiments performed with light indicate that light exhibits
(1) particle properties only
(2) wave properties only
(3) both particle and wave properties
(4) neither wave nor particle properties

11. A photon of light carries
(1) energy, but not momentum
(2) momentum, but not energy
(3) both energy and momentum
(4) neither energy nor momentum

Early Models of the Atom

An **atom** is the smallest particle of an element that retains the characteristics of the element. Models for the structure of the atom have evolved over centuries as scientists have developed more sophisticated methods and equipment for studying particles that are too small to be detected by the unaided eye.

Thomson's Model

Over 100 years ago, J. J. Thomson discovered that electrons are relatively low-mass, negatively charged particles present in atoms. Because he knew that atoms are electrically neutral, Thomson concluded that part of the atom must possess a positive charge equal to the total charge of the atom's electrons. Thomson proposed a model in which the atom consists of a uniform distribution of positive charge in which electrons are embedded, like raisins in plum pudding.

Rutherford's Model

Less than two decades later, Ernest Rutherford proposed a different model of the atom. He performed experiments in which he directed a beam of massive, positively charged particles, traveling at approximately 5% of the speed of light, at extremely thin gold foil. Rutherford postulated that if an atom was like those described in Thomson's model, there would be only small net Coulomb forces on a positively charged particle as it passed through or near a gold atom in the foil, and the particle would pass through the foil relatively unaffected. However, he found that, although nearly all the positively charged particles were not deflected from a straight-line path through the gold foil, a small number of particles were scattered at large angles.

To explain the large angles of deflection of those few particles, Rutherford theorized that the massive, energetic, positively charged particles must have collided with other even more massive positively charged particles. Assuming that atoms are symmetrical, he concluded that this concentration of mass and positive charge in the atom, which he called the nucleus, is located at the atom's center. From the relative number of deflected particles, he calculated that the nucleus is only about $\frac{1}{10,000}$ the diameter of the average atom.

Based on the results of these scattering experiments, Rutherford described an atom as being similar to a miniature solar system. The tiny nucleus at the center of the atom contains all the positive charge of the atom and virtually all of its mass. The nucleus is surrounded by enough electrons to balance the positive charge of the nucleus and make the atom electrically neutral. The electrons move in orbits around the nucleus and are held in orbit by Coulomb forces of attraction between their negative charges and the positive charge of the nucleus.

In Rutherford's model, the electrons orbiting the nucleus accelerate due to a change in direction of motion. Rutherford knew that these accelerated charges should radiate electromagnetic energy, lose kinetic energy and momentum in the process, and spiral rapidly to the nucleus. The radiated electromagnetic energy would increase in frequency and produce a continuous spectrum. This expected behavior is contradicted by the observed bright-line spectrum that is characteristic of each element. (Bright-line spectra will be discussed later in this topic.)

The Bohr Model of the Hydrogen Atom

About two years later, Niels Bohr attempted to explain why electrons in atoms can maintain their positions outside the nucleus rather than spiral into the nucleus and cause the atom to collapse. Bohr developed a model of the hydrogen atom based on these assumptions:

- All forms of energy are **quantized,** that is, an electron can gain or lose kinetic energy only in fixed amounts, or quanta.
- The electron in the hydrogen atom can occupy only certain specific orbits of fixed radius and no others.
- The electron can jump from one orbit to a higher one by absorbing a quantum of energy in the form of a photon.
- Each allowed orbit in the atom corresponds to a specific amount of energy. The orbit nearest the nucleus represents the smallest amount of energy that the electron can have. The electron can remain in this orbit without losing energy even though it is being constantly accelerated toward the nucleus by the Coulomb force of attraction.

When the electron is in any particular orbit, it is said to be in a **stationary state.** Each stationary state represents a specific amount of energy and is called an **energy level.** The successive energy levels of the hydrogen atom are assigned integral numbers, denoted by $n = 1$, $n = 2$, etc. When the electron is in the lowest energy level ($n = 1$), the atom is said to be in the **ground state.** When the electron is in any level above $n = 1$, the atom is said to be in an **excited state.**

Energy Levels Any process that raises the energy level of electrons in an atom is called <u>excitation</u>. Excitation can be the result of absorbing the energy of colliding particles of matter, such as electrons, or of photons of electromagnetic radiation. A photon's energy is absorbed by an electron in an atom only if the photon's energy corresponds exactly to an energy-level difference possible for the electron. Excitation energies are different for different elements.

Atoms rapidly lose the energy of their various excited states as their electrons return to the ground state. This lost energy is in the form of photons (radiation) of specific frequencies, which appear as spectral lines in the characteristic spectrum of each element. A **spectral line** is a particular frequency of absorbed or emitted energy characteristic of an atom.

Ionization Potential An atom can absorb sufficient energy to raise an electron to an energy level such that the electron is essentially removed from the atom and an ion is formed. The energy required to remove an electron from an atom to form an ion is called the atom's **ionization potential.** An atom in an excited state requires a smaller amount of energy to become an ion than does an atom in the ground state.

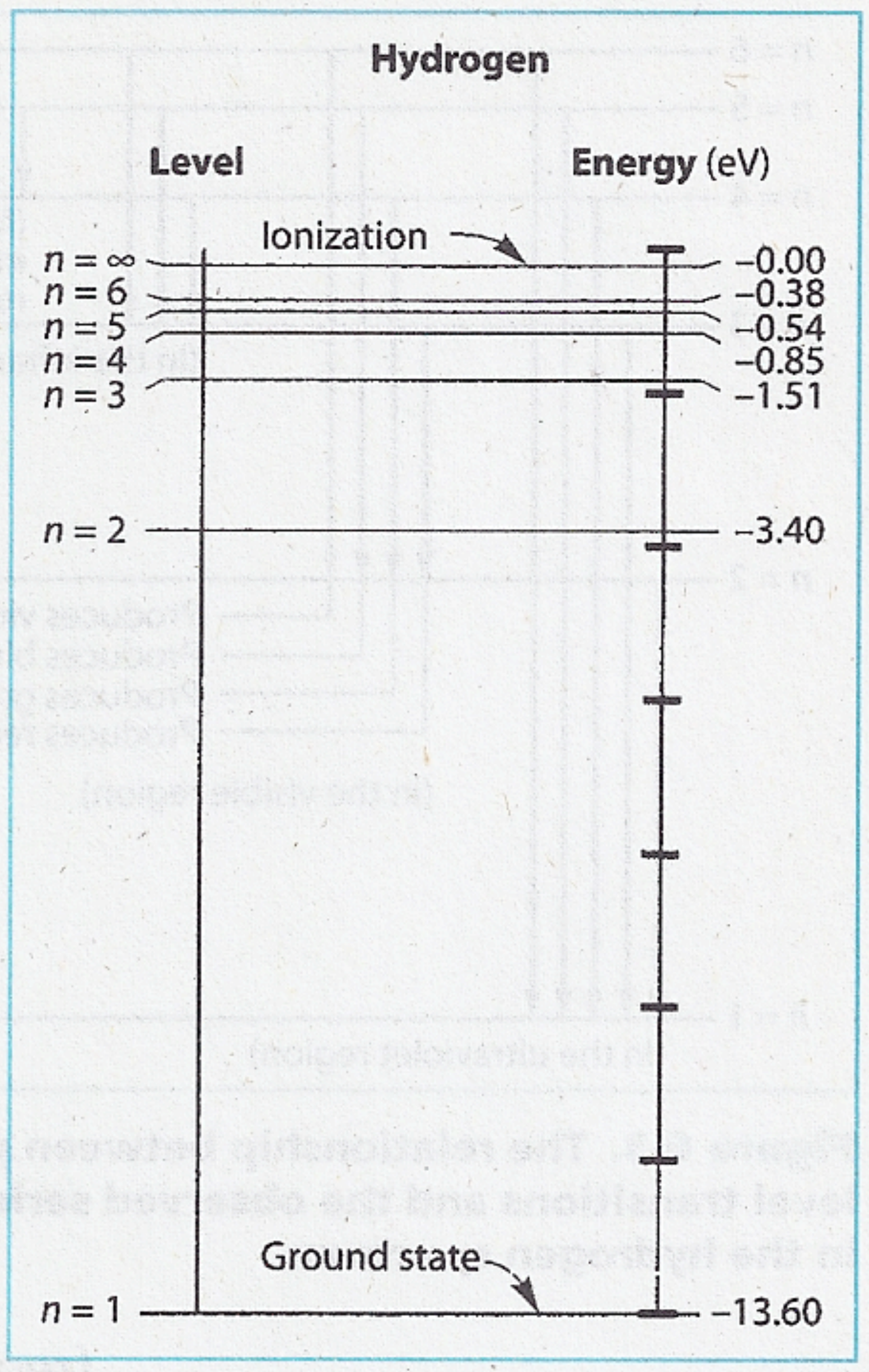


Figure 6-2. Energy levels for the hydrogen atom

Figure 6-2 shows the energy-level diagram for the hydrogen atom. An **energy-level diagram** is one in which the energy levels of a quantized system are indicated by distances of horizontal lines from a zero energy level. The energy level of an electron that has been completely removed from the atom ($n = \infty$) is defined to be 0.00 eV. Thus, all other energy levels have negative values. As an electron moves closer to the nucleus, the energy associated with the electron becomes smaller. Because an electron in the ground state has the lowest energy, its energy has the largest negative value. The *Physics Reference Tables for Physical Setting/Physics* contain energy level diagrams for hydrogen and mercury.

Limitations of Bohr's Model Although Bohr's model explained the spectral lines of hydrogen, it could not predict the spectra or explain the electron orbits of elements having many electrons. Nevertheless, Bohr's model with its quantized energy levels set the stage for future atomic models.

The Cloud Model

Bohr's model of the atom has been replaced by the cloud model. In this model, electrons are not confined to specific orbits. Instead, they are spread out in space in a form called an electron cloud. The electron cloud is densest in regions where the probability of finding the electron is highest. Complicated equations describe the shape, location, and density of each electron cloud in an atom. Each cloud corresponds to a particular location for an electron. By incorporating the cloud model into the Rutherford-Bohr model, scientists have been able to construct accurate models of the electron arrangements for all the elements.

Atomic Spectra

When the electrons in excited atoms of an element in the gaseous state return to lower energy levels, they produce a specific series of frequencies of electromagnetic radiation called the **atomic spectrum** of the element. Each element has a characteristic spectrum that differs from that of every other element. Thus, the spectrum can be used to identify the element, even when the element is mixed with other elements.

The element helium was found on the Sun before it was isolated on Earth. Spectral lines of the Sun's corona were studied during a solar eclipse. The lines were not previously reported for any known element, so the new element was named helium from the Greek word for sun, *helios*.

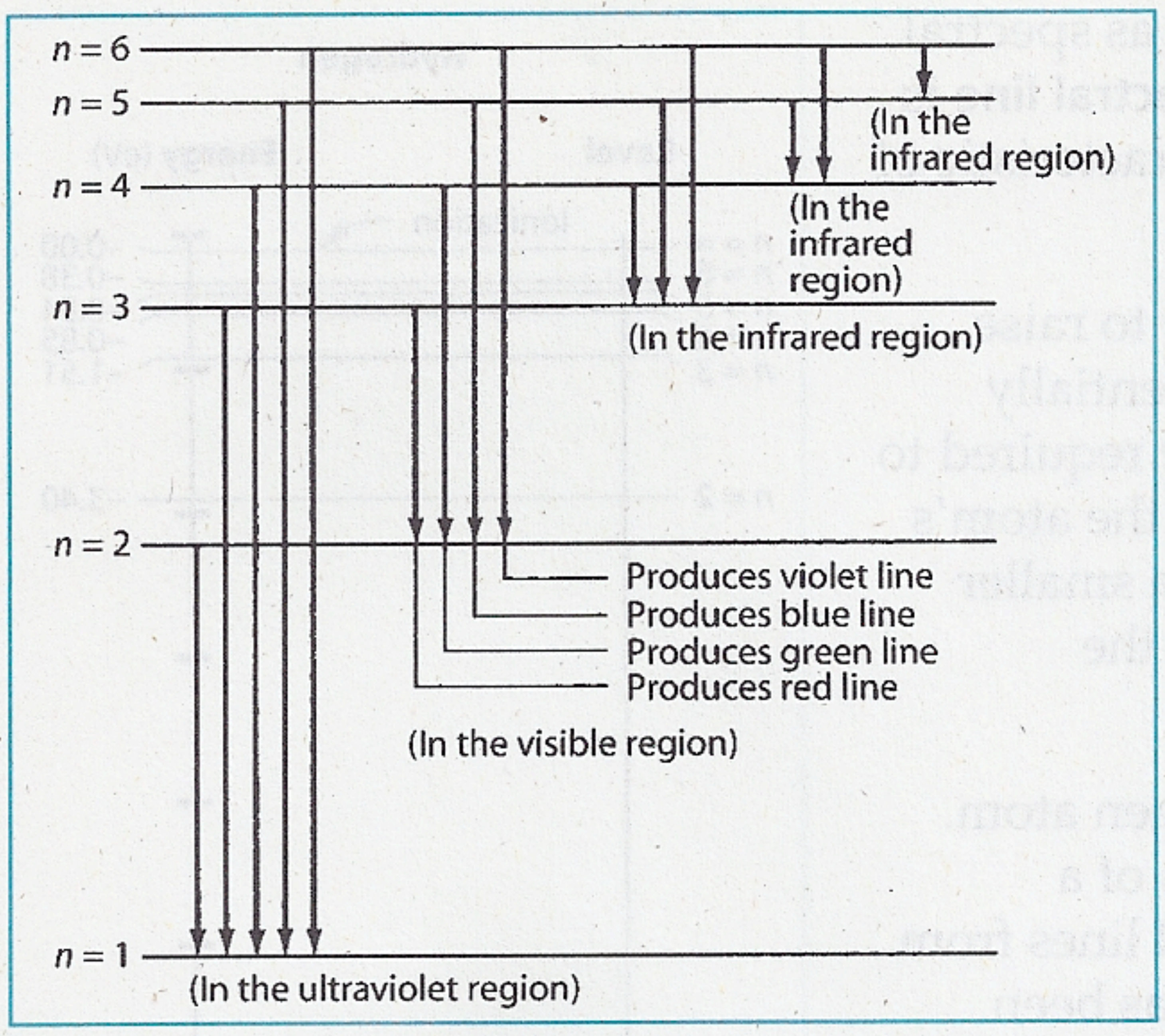


Figure 6-3. The relationship between possible energy level transitions and the observed series of frequencies in the hydrogen spectrum

Emission (Bright-Line) Spectra

Energy levels in an atom, introduced by Bohr, provided an explanation for atomic spectra. When an electron in an atom in an excited state falls to a lower energy level, the energy of the emitted photon is equal to the difference between the energies of the initial and final states. That is

$$E_{photon} = E_i - E_f$$

where E_i is the initial energy of an electron in the higher energy level and E_f is the final energy of the electron in the lower energy level. Each energy difference between two energy levels corresponds to a photon having a specific frequency. A specific series of frequencies, characteristic of the element, is produced when the electrons of its atoms in excited states fall to lower energy levels and the atoms return to lower states or to the ground state. When these emitted frequencies are viewed in a spectroscope, the frequencies appear as a series of bright lines against a dark background and, therefore, are called a **bright-line spectrum** or an **emission spectrum.** In Figure 6-3 the energy emissions producing various series of lines in the ultraviolet, visible light, and infrared regions are indicated in the energy-level diagram for hydrogen.

Absorption Spectra

As explained earlier, an atom can absorb only photons having energies equal to specific differences in its energy levels. The frequencies and wavelengths of these absorbed photons are exactly the same as those of the photons emitted when electrons lose energy and fall between the same energy levels. If the atoms of an element are subjected to white light, which consists of all the visible frequencies, the atoms will selectively absorb the same frequencies that they emit when excited. The absorbed frequencies appear as dark lines in the otherwise continuous white-light spectrum. This series of dark lines, resulting from the selective absorption of particular frequencies in the white-light spectrum of an atom, is called an **absorption spectrum.** An atom will absorb a photon only if the photon possesses the exact amount of energy required to raise the atom to one of its possible excited states.

Review Questions

12. The lowest energy state of an atom is called its

(1) ground state
(2) ionized state
(3) initial energy state
(4) final energy state

13. Which electron transition in the hydrogen atom results in the emission of a photon with the greatest energy?

(1) $n = 2$ to $n = 1$
(2) $n = 3$ to $n = 2$
(3) $n = 4$ to $n = 2$
(4) $n = 5$ to $n = 3$

14. What is the minimum energy required to ionize a hydrogen atom in the $n = 3$ state?

(1) 13.60 eV
(2) 12.09 eV
(3) 5.52 eV
(4) 1.51 eV

15. Which photon energy could be absorbed by a hydrogen atom that is in the $n = 2$ state?

(1) 0.66 eV
(2) 1.51 eV
(3) 1.89 eV
(4) 2.40 eV

16. Hydrogen atoms undergo a transition from the $n = 3$ excited state to the ground state. What is the total number of different photon energies that may be emitted by these atoms?

17. An electron in a mercury atom jumps from level *a* to level *g* by absorbing a single photon. Determine the energy of the photon in joules.

18. Which phenomenon provides evidence that the hydrogen atom has discrete energy levels?

19. A photon having an energy of 9.40 electronvolts strikes a hydrogen atom in the ground state. Why is the photon *not* absorbed by the hydrogen atom?

(1) The atom's orbital electron is moving too fast.
(2) The photon striking the atom is moving too fast.
(3) The photon's energy is too small.
(4) The photon is being repelled by electrostatic force.

20. Which transition between the energy levels of a mercury atom causes the emission of a photon of highest frequency?

(1) *e* to *d* (2) *e* to *c* (3) *c* to *b* (4) *b* to *a*

21. White light is passed through a cloud of cool hydrogen gas and then examined with a spectroscope. The dark lines observed on a bright background are caused by

(1) the hydrogen emitting all frequencies in the white light
(2) the hydrogen absorbing certain frequencies of the white light
(3) diffraction of the white light
(4) constructive interference

22. It is possible for an excited hydrogen atom to return to the ground state by the emission of a single photon. Regardless of the initial excited state, this electron transition produces a spectral line in which region of the electromagnetic spectrum?

(1) ultraviolet (3) visible light
(2) infrared (4) radio waves

23. An electron in a mercury atom changes from energy level *b* to level e. This energy-level change occurs as the atom

(1) absorbs a 2.03-eV photon
(2) absorbs a 5.74-eV photon
(3) emits a 2.03-eV photon
(4) emits a 5.74-eV photon

Base your answers to questions 24 through 26 on the information that follows.

A hydrogen atom emits a 2.55-electronvolt photon as its electron changes from one energy level to another.

24. Determine the energy level change for the electron.

25. Express the energy of the emitted photon in joules.

26. Calculate the frequency of the emitted photon.

Base your answers to questions 27 through 29 on the information below.

The light of the "alpha line" in the Balmer series of the hydrogen spectrum has a wavelength of 6.58×10^{-7} meter in air.

27. Calculate the energy of an "alpha line" photon in joules.

28. What is the energy of an "alpha line" photon in electronvolts?

29. Using your answer to question 28, explain whether or not this result verifies that the "alpha line" corresponds to a transition from energy level $n = 3$ to energy level $n = 2$ in a hydrogen atom.

Base your answers to questions 30 through 33 on the following information.

A photon with 14.60 electronvolts of energy collides with a mercury atom in its ground state.

30. Express the energy of the incident photon in joules.

31. Calculate the frequency of the incident photon.

32. In what region of the electromagnetic spectrum is the frequency of the incident photon?

(1) gamma rays (3) visible
(2) infrared (4) ultraviolet

33. If the photon collision ionizes the atom, what is the maximum energy that the electron removed from the atom can have?

(1) 0.00 eV (3) 10.38 eV
(2) 4.22 eV (4) 14.60 eV

34. Calculate the frequency of the photon emitted when the electron in an excited hydrogen atom changes from energy level $n = 3$ to $n = 2$.

The Nucleus

Rutherford's experiments showed that all of the atom's positive charge and nearly all of its mass is contained in the nucleus. The **nucleus** is the core of an atom made up of one or more protons and (except for one of the isotopes of hydrogen) one or more neutrons. The protons and neutrons that make up the nucleus of an atom are called nucleons.

Strong Nuclear Force

The positively charged protons in any nucleus containing more than one proton are separated by a distance of 10^{-15} meter. Consequently, a large repulsive Coulomb force exists between them. The gravitational force of attraction between protons is far too weak to counterbalance this electrostatic force of repulsion. Thus, there must exist a very strong attractive nuclear force to keep the protons concentrated in the nucleus of an atom. It is this **strong nuclear force,** which is an attractive force between protons and neutrons in an atomic nucleus, that is responsible for the stability of the nucleus.

The strong nuclear force of attraction between two protons in a nucleus is about 100 times stronger than the electrostatic force of repulsion. At distances greater than a few nucleon diameters, however, the strong nuclear force diminishes rapidly and becomes much less than the gravitational or electrostatic forces. Although the strong nuclear force is the strongest force known to exist, it is effective only over a short distance.

Universal Mass Unit

The mass of an individual atom is a very small fraction of a kilogram. Consequently, for convenience, scientists use another unit called the universal mass unit, u, to express such masses. The **universal mass unit,** or atomic mass unit, is defined as $\frac{1}{12}$ the mass of an atom of carbon-12, which is a carbon atom having 6 protons, 6 neutrons, and 6 electrons. In universal mass units, the mass of the proton is 1.0073 u, the mass of the neutron is 1.0087 u, and the mass of an electron is 0.0005 u. In SI units, a mass of one universal mass unit, or 1 u, equals 1.66×10^{-27} kilogram.

Mass-Energy Relationship

Einstein showed that mass and energy are different forms of the same thing and are equivalent. The energy equivalent of mass is directly proportional to both the mass and the speed of light in a vacuum squared. The following formula expresses this relationship.

$$E = mc^2$$ Ⓡ

Energy E is in joules, mass m is in kilograms, and c is the speed of light in a vacuum, 3.00×10^8 meters per second. For example, if one kilogram of mass is converted to energy, the amount of energy produced is 9.00×10^{16} joules. Thus, the masses of subatomic particles can be expressed in joules, but more often they are expressed in an equivalent number of electronvolts.

SAMPLE PROBLEM

One universal mass unit equals 1.66×10^{-27} kilogram. Calculate the energy equivalent of one universal mass unit in megaelectronvolts.

SOLUTION: Identify the known and unknown values.

Known
$m = 1.66 \times 10^{-27}$ kg
$c = 3.00 \times 10^{8}$ m/s
$1 \text{ eV} = 1.60 \times 10^{-19}$ J
$10^6 \text{ eV} = 1$ MeV

Unknown
$E = ?$ MeV

1. Write the formula that relates energy and mass.

$$E = mc^2$$

2. Substitute the known values and solve.

$$E = (1.66 \times 10^{-27} \text{ kg})(3.00 \times 10^{8} \text{ m/s})^2$$
$$E = 1.49 \times 10^{-10} \text{ J}$$

3. Use the relationship between electronvolts and joules to convert the energy in joules to electronvolts.

$$E = (1.49 \times 10^{-10} \text{ J})\left(\frac{1 \text{ eV}}{1.60 \times 10^{-19} \text{ J}}\right)$$
$$E = 9.31 \times 10^{8} \text{ eV}$$

4. Use the relationship between eV and Mev to convert eV to MeV.

$$E = (9.31 \times 10^{8} \text{ eV})\left(\frac{1 \text{ MeV}}{10^6 \text{ eV}}\right)$$
$$E = 931 \text{ MeV}$$

Nuclear Mass and Energy

According to Einstein's mass-energy equation, any change in energy results in an equivalent change in mass. Mass-energy is conserved at all levels from cosmic to subatomic. For example, in a chemical reaction in which one kilogram of carbon combines with oxygen to form carbon dioxide, the amount of energy released is 3.3×10^7 joules. Even though this is a significant amount of energy, it is equivalent to only 4×10^{-10} kilogram of mass. The mass of the carbon dioxide formed in the reaction is slightly less than the mass of the carbon and oxygen before they reacted. This change in mass is too small to detect or measure. The same is true for all chemical reactions and other ordinary energy changes. However, in reactions involving the nuclei of atoms, the changes in energy relative to the masses involved are much larger, and the corresponding changes in mass can be measured.

The mass of a proton is 1.0073 u and the mass of a neutron is 1.0087 u. Thus, the total mass of two protons and two neutrons is 2(1.0073 u + 1.0087 u), or 4.0320 u. However, the mass of a helium-4 nucleus, which consists of two protons and two neutrons, is only 4.0016 u. Thus, the mass of the atomic nucleus is less than the sum of the masses of its individual nucleons when measured separately. This is true of every nucleus, with the exception of hydrogen-1, which has only one nucleon.

When nucleons come together to form a nucleus, energy is released and an equivalent amount of matter is lost. To break up the nucleus and separate the nucleons, work must to be done against the strong nuclear force of attraction. The energy needed to separate the nucleons appears as an equivalent increase in their total mass.

SAMPLE PROBLEM

A helium nucleus consisting of two protons and two neutrons has a mass of 4.0016 universal mass units. The mass of a proton is 1.0073 universal mass units and the mass of a neutron is 1.0087 universal mass units.

(a) Find the difference between the mass of the helium nucleus and the total mass of its constituents.

(b) Find the energy equivalent of this mass difference in electronvolts.

SOLUTION: Identify the known and unknown values.

Known	*Unknown*
mass of helium nucleus = 4.0016 u	mass difference = ? u
mass of proton = 1.0073 u	E = ? eV
mass of neutron = 1.0087 u	
1 u = 931 MeV	

1. Determine the mass of the two protons and two neutrons.

mass of 2 protons = 2(1.0073 u) = 2.0146 u
mass of 2 neutrons = 2(1.0087 u) = 2.0174 u

Find the total mass of the four individual nucleons.
total mass = 2.0146 u + 2.0174 u = 4.0320 u

Find the difference between the masses of the individual nucleons and a helium nucleus.
mass difference = 4.0320 u − 4.0016 u = 0.0304 u

2. Use the relationship between the universal mass unit and MeV, 1 u = 931 MeV.

E = (0.0304 u)(931 MeV/u) = 28.3 MeV

Studying Atomic Nuclei

The structure of the atomic nucleus and the nature of matter have been investigated using particle accelerators. These devices use electric and magnetic fields to increase the kinetic energies of charged particles, such as electrons and protons, and project them at speeds near the speed of light in a vacuum into samples of matter. Collisions between the high speed particles and atomic nuclei may disrupt the nuclei and release new particles. The study of these ejected particles can give useful information about the structure and forces within the nucleus. Scientists continue to study the atomic nucleus because the nucleus, and thus the atomic structure of an atom of an element determines the particular physical and chemical properties of the element. Each type of atom is different and distinct. A growing understanding of nuclear forces and structure will increase understanding of matter and its interactions.

Review Questions

35. Which particles are most likely to be found in an atomic nucleus?
(1) neutrons, only
(2) protons, only
(3) both protons and neutrons
(4) both neutrons and electrons

36. Which description of the interaction which binds a nucleus together is most accurate?
(1) long-range and weak
(2) long-range and strong
(3) short-range and weak
(4) short-range and strong

37. What force holds protons and neutrons together in an atom?

(1) strong force (3) gravitational force
(2) magnetic force (4) electrostatic force

38. Which fundamental force is primarily responsible for the attraction between protons and electrons?

(1) strong (3) gravitational
(2) weak (4) electromagnetic

39. The energy produced by the complete conversion of 2.0×10^{-5} kilogram of mass into energy is

(1) 1.8 TJ (2) 6.0 GJ (3) 1.8 MJ (4) 6.0 kJ

40. In the equation $E = mc^2$, E may be expressed in

(1) newtons/coulomb (3) electronvolts
(2) joules/second (4) coulombs

41. If a deuterium nucleus has a mass of 1.53×10^{-3} universal mass unit less than its components, this mass represents an energy of

(1) 1.38 MeV (3) 1.53 MeV
(2) 1.42 MeV (4) 3.16 MeV

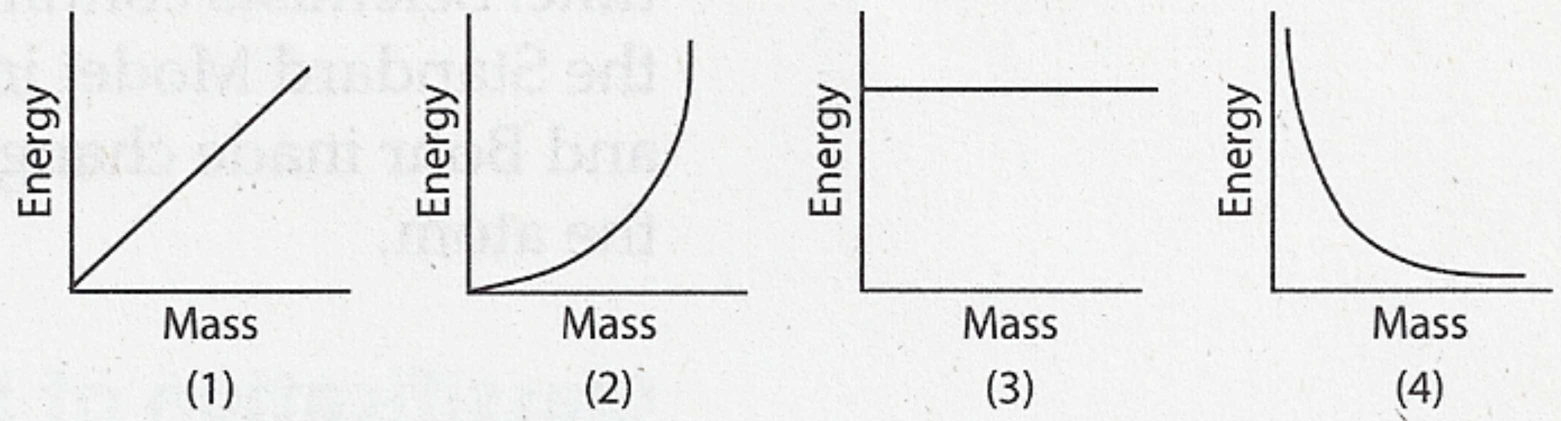
42. Calculate the amount of energy in joules that would be produced if 2.50×10^{-3} kilogram of matter was entirely converted to energy.

43. If the mass of one proton was totally converted into energy, the yield would be

(1) 2.79×10^{-38} J (3) 1.50×10^{-10} J
(2) 5.01×10^{-19} J (4) 9.00×10^{16} J

44. In a nuclear reaction, 9.90×10^{-13} joule of energy was released. Calculate the mass equivalent of this energy.

45. Which graph best represents the relationship between energy and mass when matter is converted into energy?



46. The chart below shows the masses of selected particles.

Particle	Mass
$^{235}_{92}U$	235.0 u
$^{138}_{56}Ba$	137.9 u
$^{95}_{36}Kr$	94.9 u
$^{1}_{0}n$	1.0 u

Consider the following equation.

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{138}_{56}Ba + ^{95}_{36}Kr + 3^{1}_{0}n + E$$

The energy E is equivalent to a mass of

(1) 0.2 u (2) 2.0 u (3) 2.2 u (4) 0.0 u

The Standard Model of Particle Physics

Today, particle physicists are in the process of building a model of the structure of the nucleus. The current model, called the **Standard Model of Particle Physics,** is a theory, not a law, that is used to explain the existence of all the particles that have been observed and the forces that hold atoms together or lead to their decay.

The Fundamental Forces in Nature

Force can be defined as a push or pull on a mass, or explained as a vector quantity causing an object to accelerate. In modern physics, scientists refer to particles as force carriers, because forces are brought about as a result of an exchange of particles.

There are four fundamental forces in nature: strong (nuclear), electromagnetic, weak, and gravitational. Table 6-1 gives an overview of the important characteristics of these four forces. The weak force, which has not yet been discussed, is another short-range nuclear force that is responsible for the decay of some nuclear particles.

Table 6-1. The Fundamental Forces of Nature

Force	Relative Strength	Range of Force
strong (nuclear)	1	$\approx 10^{-15}$ m
electromagnetic	10^{-2}	proportional to $\frac{1}{r^2}$
weak	10^{-13}	$<10^{-18}$ m
gravitational	10^{-38}	proportional to $\frac{1}{r^2}$

Electric and magnetic forces are often treated independently, but they are actually combined as electromagnetic force. The weak force has successfully been combined with the electromagnetic force to produce a single electroweak force. Grand unification theories (GUTs) attempt to add the strong force to this combination. Theories of everything (TOEs), which would combine gravity with all the other forces, are not developed at this time. Scientists continue to try to resolve questions and inconsistencies in the Standard Model in much the same manner as Thomson, Rutherford, and Bohr made changes and amendments to the model for the structure of the atom.

Classification of Subatomic Particles

Particles can be classified according to the types of interactions they have with other particles. If the force carrier particles are excluded, all particles can be classified into two groups according to the types of interactions they have with other particles. A particle that interacts through the strong nuclear force, as well as the electromagnetic, weak, and gravitational forces, is called a **hadron.** Protons and neutrons are hadrons. A particle that interacts through the electromagnetic, weak, and gravitational forces, but *not* the strong nuclear force, is called a **lepton.** A lepton has a mass less than that of a proton. Electrons, positrons, and neutrinos are classified as leptons. A **positron** is a particle whose mass is equal to the mass of the electron, and whose positive electric charge is equal in magnitude to the negative charge of the electron. A **neutrino** is a neutral particle that has little, if any, mass but does possess both energy and momentum. The *Reference Tables for Physical Setting/Physics* give the names, symbols, and charges of the six members of the lepton family. Ⓡ

The hadron group can be subdivided into baryons and mesons. A **baryon** is an elementary particle that can be transformed into a proton or neutron and some number of mesons and lighter particles. Baryons are also known as heavy particles because their masses are equal to or greater than the mass of a proton. A **meson** is a particle of intermediate mass. Mesons decay into electrons, positrons, neutrinos, and photons.

An antiparticle is associated with each particle. An **antiparticle** is a particle having mass, lifetime, and spin identical to the associated particle, but with charge of opposite sign (if charged) and magnetic moment reversed in sign. An antiparticle is denoted by a bar over the symbol for the particle. For example, an antiproton, the antiparticle of a proton p, is denoted by the symbol $\bar{p}$. Thus, the antiproton would be described as a stable baryon carrying a unit negative charge, but having the same mass as a proton. The positron, noted earlier, is thus the antiparticle of the electron. The antineutron, the antiparticle of the neutron, has the same mass as the neutron and is also electrically neutral. However the magnetic moment and spin of the antineutron are in the same direction, whereas, the magnetic moment and spin of the neutron are in opposite directions. An antiparticle exists for the neutrino; the two are identical except for their direction of spin. **Antimatter** is material consisting of atoms that are composed of antiprotons, antineutrons, and positrons.

The Quark Baryons and mesons are composed of more fundamental particles called quarks. A **quark** is one of the basic particles, having charges of $\pm\frac{1}{3}$e or $\pm\frac{2}{3}$e, from which many of the elementary particles may be built up. This implies that the charge on the electron is no longer considered to be the smallest nonzero charge that a particle may possess. The quarks are named *up, down, charm, strange, top,* and *bottom*. Every baryon is a combination of three quarks and every meson is a combination of a quark and an antiquark. An **antiquark** is the antiparticle of a quark, having electric charge, baryon number, and strangeness opposite in sign to that of the corresponding quark. An antibaryon consists of three antiquarks. The *Reference Tables for Physical Setting/Physics* give the names, symbols, and charges of the six members of the quark family. The quark content of a proton is *uud* (up, up, down) and the quark content of a neutron is *udd* (up, down, down). When quarks combine to form baryons, their charges add algebraically to a total of 0e, +1e, or −1e. When quarks and antiquarks combine to form mesons, their charges add algebraically to a total of 0e, +1e, or −1e.

Review Questions

Base your answers to questions 47 through 49 on information given in Table 6-1.

47. Express the range of the strong force in picometers.

48. Express the range of the weak force in nanometers.

49. How many times stronger than the gravitational force is the electromagnetic force?

50. What is the total number of quarks in a helium nucleus consisting of 2 protons and 2 neutrons?

(1) 16 (2) 12 (3) 8 (4) 4

Base your answers to questions 51 and 52 on the information and equation below.

During the process of beta (β^-) emission, a neutron in the nucleus of an atom is converted into a proton, an electron, an electron antineutrino, and energy.

neutron → proton + electron + electron antineutrino + energy

51. Based on conservation laws, how does the mass of the neutron compare to the mass of the proton?

52. Since charge must be conserved in the reaction shown, what charge must an electron antineutrino carry?

53. A baryon may have a charge of

(1) $-\frac{1}{3}$e (2) 0 e (3) $+\frac{2}{3}$e (4) $+\frac{4}{3}$e

54. An antibaryon is composed of

(1) three quarks
(2) one quark and two antiquarks
(3) three antiquarks
(4) two quarks and one antiquark

55. What is the electric charge on a pion having quark composition $u\bar{d}$?

56. What is the electric charge on a particle having quark composition $d\bar{b}$?

57. A particle has a quark composition of *dds*. What is the charge on and classification of the particle?

(1) −1e, baryon (3) −1e, meson
(2) +1e, baryon (4) +1e, meson

58. A particle has a quark composition of $s\bar{u}$. What is the charge on and classification of the particle?

(1) −1e, baryon
(2) +1e, baryon
(3) −1e, meson
(4) +1e, meson

59. What is the mass of an antineutron in kilograms?

Practice Questions *for the* New York Regents Exam

Directions

Review the Test-Taking Strategies section of this book. Then answer the following questions. Read each question carefully and answer with a correct choice or response.

Part A

1 A photon of light traveling through space with a wavelength of 6.0×10^{-7} meter has an energy of
(1) 4.0×10^{-40} J
(2) 3.3×10^{-19} J
(3) 5.4×10^{10} J
(4) 5.0×10^{14} J

2 The energy of a photon varies directly with its
(1) frequency
(2) wavelength
(3) speed
(4) rest mass

3 A variable-frequency light source emits a series of photons. As the frequency of the photon increases, what happens to the energy and wavelength of the photon?
(1) The energy decreases and the wavelength decreases.
(2) The energy decreases and the wavelength increases.
(3) The energy increases and the wavelength decreases.
(4) The energy increases and the wavelength increases.

4 When a photon and a free electron collide there is conservation of
(1) velocity, only
(2) both velocity and energy
(3) momentum, only
(4) both momentum and energy

5 The concept that electrons exhibit wave properties can best be demonstrated by the
(1) collisions between photons and electrons
(2) existence of an electron antiparticle
(3) production of electron interference patterns
(4) classification of the electron as a lepton

6 The bright-line emission spectrum of an element can best be explained by
(1) electrons transitioning between discrete energy levels in the atoms of that element
(2) protons acting as both particles and waves
(3) electrons being located in the nucleus
(4) protons being dispersed uniformly throughout the atoms of that element

7 A hydrogen atom is excited to the $n = 3$ state. In returning to the ground state, the atom could *not* emit a photon with an energy of
(1) 1.89 eV
(2) 10.20 eV
(3) 12.09 eV
(4) 12.75 eV

8 During which energy level change for the electron in a hydrogen atom does the emitted photon have the shortest wavelength?
(1) $n = 5$ directly to $n = 2$
(2) $n = 4$ directly to $n = 2$
(3) $n = 2$ directly to $n = 4$
(4) $n = 2$ directly to $n = 5$

9 How much energy would be generated if a 1.00×10^{-3}-kilogram mass was completely converted to energy?
(1) 9.31×10^{-1} MeV
(2) 9.31×10^{2} MeV
(3) 9.00×10^{13} J
(4) 9.00×10^{16} J

10 The energy equivalent of the rest mass of an electron is approximately
(1) 5.1×10^{5} J
(2) 8.2×10^{-14} J
(3) 2.7×10^{-22} J
(4) 8.5×10^{-28} J

11 In the nuclear reaction

$$^{3}_{1}H + ^{1}_{1}H \rightarrow ^{4}_{2}He + \text{energy}$$

the masses of the nuclei are:

$^{1}_{1}H = 1.008\,13$ u

$^{3}_{1}H = 3.016\,95$ u

$^{4}_{2}He = 4.003\,88$ u

How much energy is released during the reaction?
(1) 3.39×10^{-21} MeV
(2) 2.12×10^{-2} MeV
(3) 1.97×10^{1} MeV
(4) 1.91×10^{15} MeV

12 Which statement is true of the strong nuclear force?
(1) It acts over very great distances.
(2) It holds protons and neutrons together.
(3) It is much weaker than gravitational forces.
(4) It repels neutral charges.

13 A meson may *not* have a charge of
(1) +1e
(2) +2e
(3) 0e
(4) −1e

TOPIC 6 Modern Physics

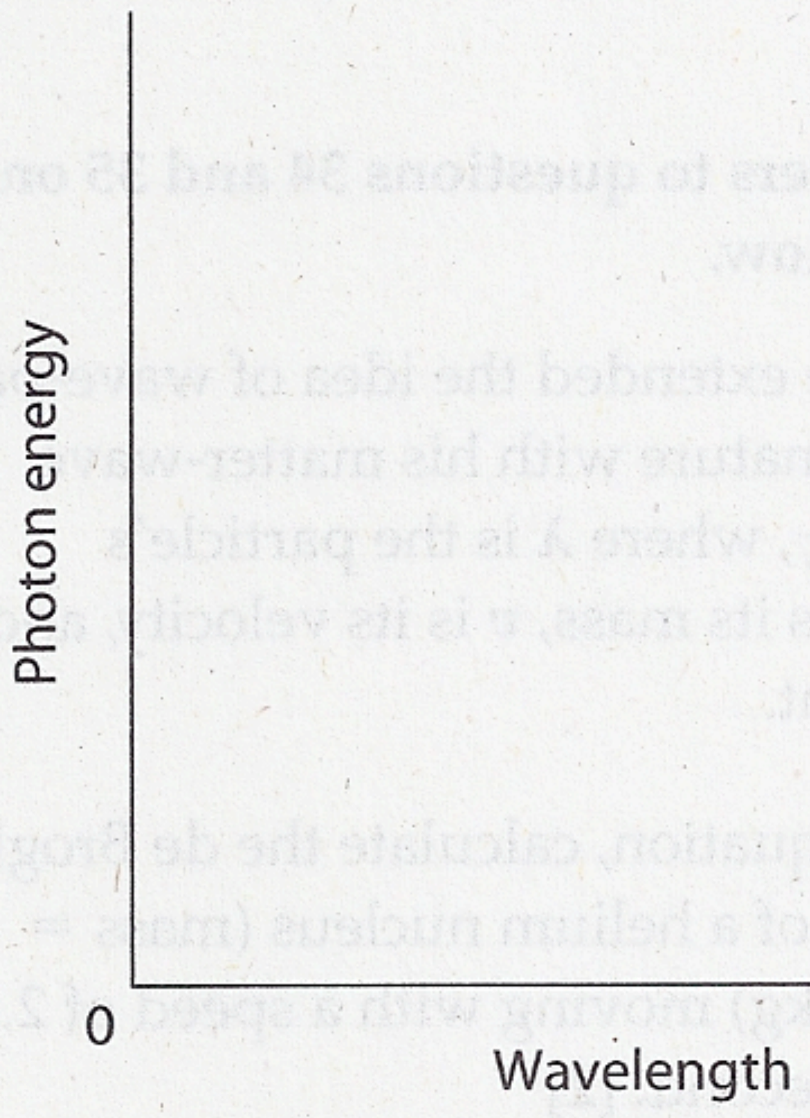
14 The charge of an antistrange quark is approximately
(1) $+5.33 \times 10^{-20}$ C (3) $+5.33 \times 10^{20}$ C
(2) -5.33×10^{-20} C (4) -5.33×10^{20} C

Part B

15 A proton has a quark content of *uud* and a neutron has a quark content of *udd*. What is the quark content of an antiproton? [1]

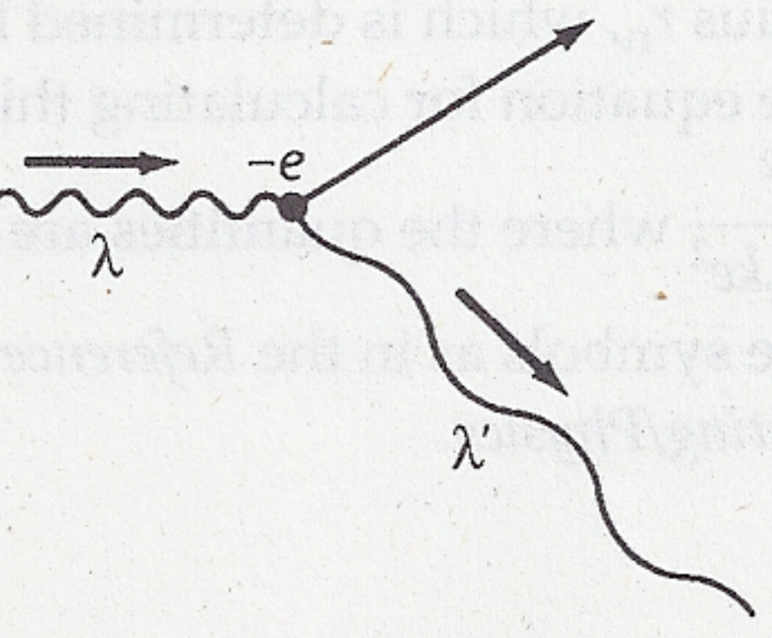
16 Calculate the energy of a photon with a frequency of 5.00×10^{15} hertz. [2]

17 On the axes below sketch a line to represent the relationship between photon energy and wavelength for a series of photons. [1]



Base your answers to questions 18 and 19 on the following information and diagram.

The diagram represents the collision of an X-ray photon having wavelength λ with an electron *-e* in an atom. The electron is ejected from the atom, and a photon having a longer wavelength λ' than the incident photon is also emitted.



18 Calculate the wavelength λ of an incident photon which has a frequency of 1.00×10^{18} hertz. [2]

19 Energy is conserved in the collision. Write an expression in terms of photon wavelength to represent the electron's increase in energy as a result of the collision. [1]

Base your answers to questions 20 through 23 on the information that follows.

An electron in a mercury atom makes a direct transition from energy level *e* to energy level *b*.

20 Determine the energy in electronvolts that is given off in this transition. [1]

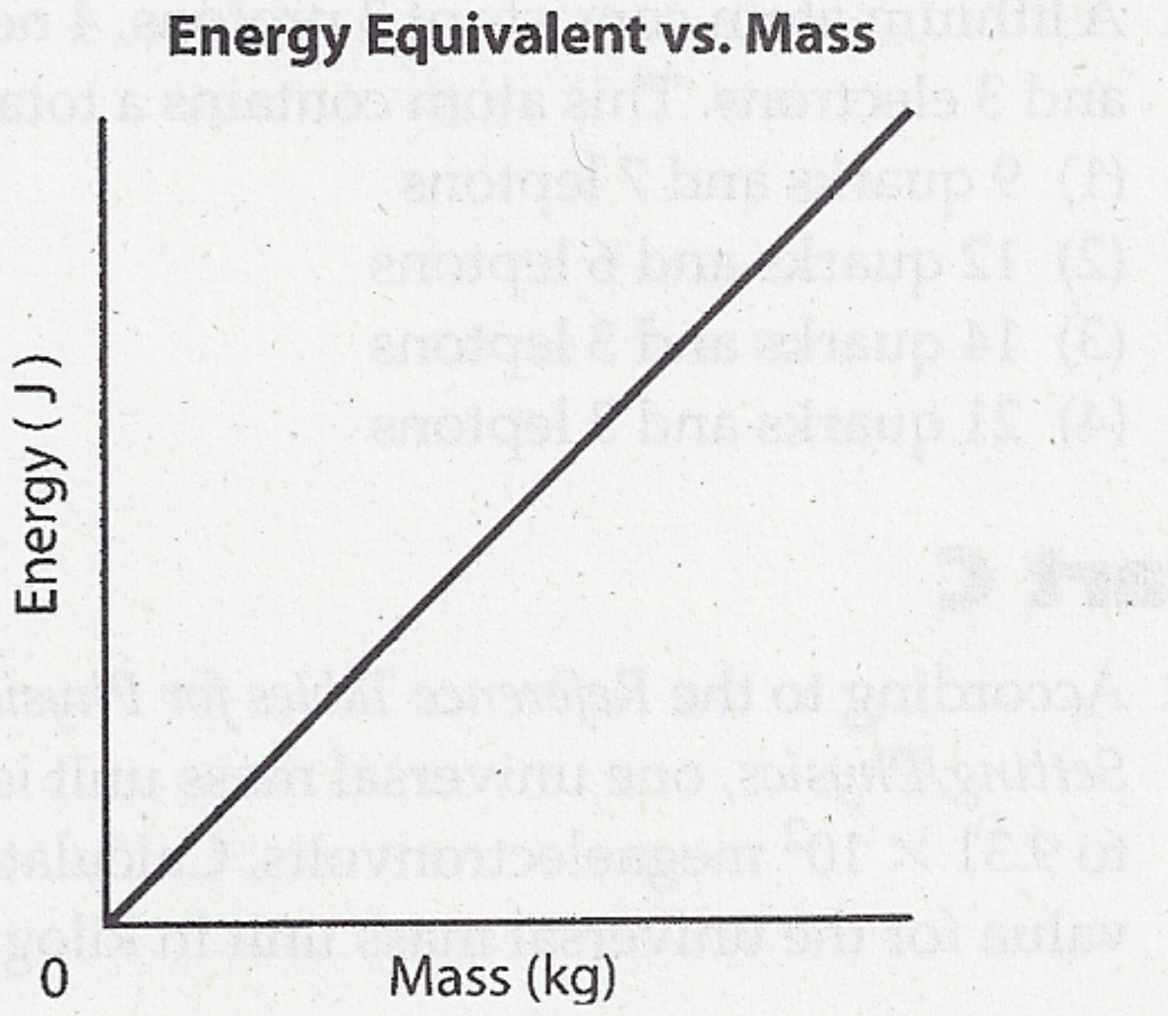
21 Determine the energy in joules of the photon emitted in the transition. [1]

22 Calculate the frequency of the radiation corresponding to the emitted photon. [2]

23 Explain what would happen if a 4.50-electronvolt photon was incident on a mercury atom in the ground state. [1]

24 An electron in a mercury atom drops from energy level *i* to the ground state by emitting a single photon. This photon has an energy of
(1) 2.50×10^{-19} J (3) 1.66×10^{-18} J
(2) 1.41×10^{-18} J (4) 1.91×10^{-18} J

25 The following graph represents the relationship between mass and its energy equivalent.



What is the physical signficance of the slope of the line? [1]

26 If c is the speed of light in a vacuum, which is an acceptable unit for the mass of a subatomic particle?
(1) GeV
(2) GeV · c
(3) GeV/c
(4) GeV/c^2

27 Express Planck's constant in fundamental units. [1]

Base your answers to questions 28 and 29 on the information in the following chart.

Particle	Rest Mass
proton	1.0073 u
neutron	1.0087 u

28 Calculate the energy equivalent of the rest mass of a neutron in megaelectronvolts. [2]

29 A tritium nucleus consists of one proton and two neutrons and has a total mass of 3.0170 universal mass units. Determine the difference in mass between the total mass of the nucleons and the mass of the tritium nucleus. [2]

---

30 A tau lepton decays into an electron, an electron antineutrino, and a tau neutrino, as represented in the reaction below.

$$\tau \rightarrow e + \bar{\nu}_e + \nu_\tau$$

Complete the equation below to show how this reaction obeys the Law of Conservation of Charge by indicating the amount of charge on each particle. [1]

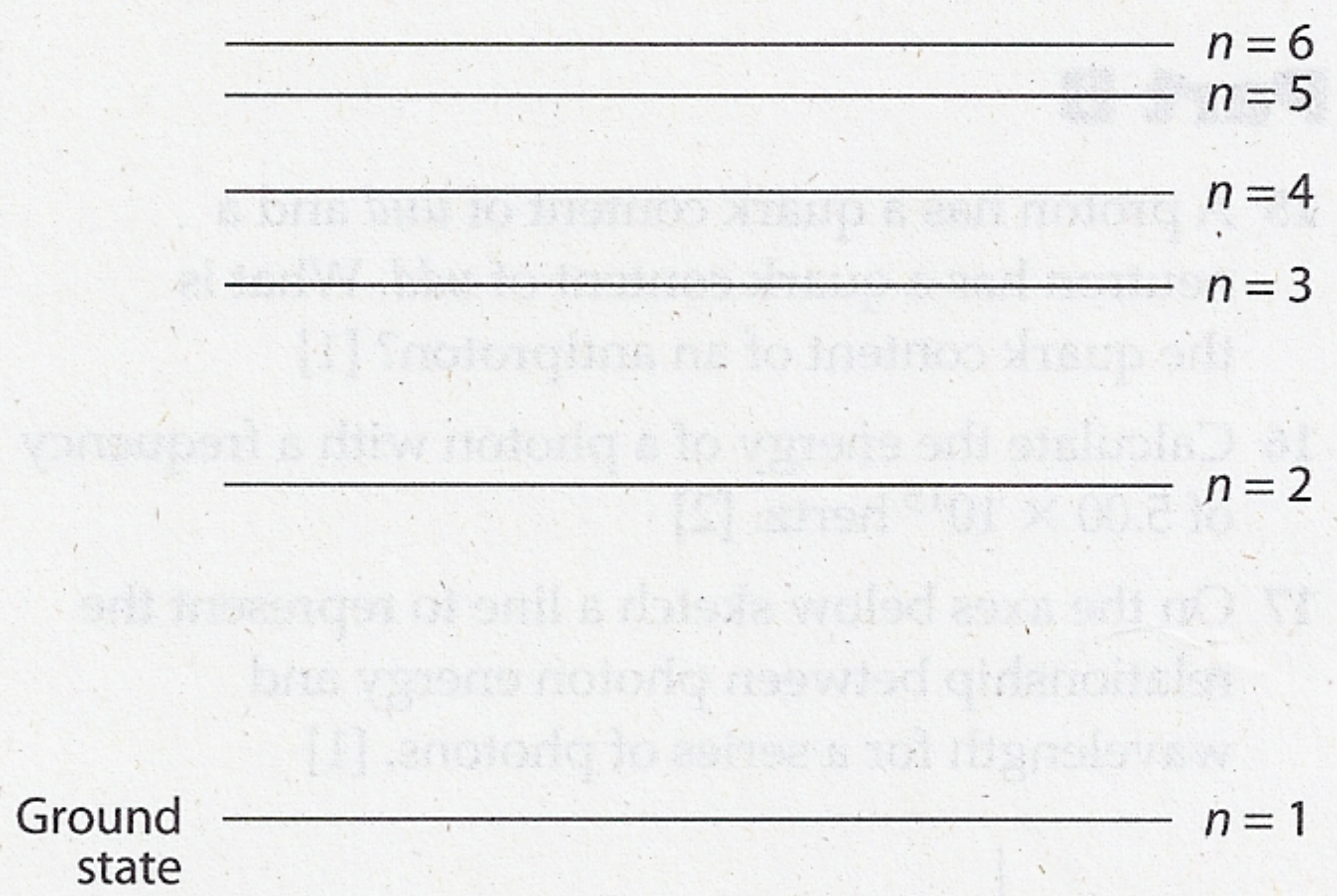
_____ e → _____ e + _____ e + _____ e

31 A lithium atom consists of 3 protons, 4 neutrons, and 3 electrons. This atom contains a total of
(1) 9 quarks and 7 leptons
(2) 12 quarks and 6 leptons
(3) 14 quarks and 3 leptons
(4) 21 quarks and 3 leptons

Part C

32 According to the *Reference Tables for Physical Setting/Physics*, one universal mass unit is equal to 9.31×10^2 megaelectronvolts. Calculate the value for the universal mass unit in kilograms. [2]

33 The diagram that follows is the energy-level diagram for a fictitious element. Draw arrows on the diagram to represent all possible electron transitions that would cause photons to be emitted from atoms of this element in the $n = 5$ excited state. [2]



Base your answers to questions 34 and 35 on the information below.

Louis de Broglie extended the idea of wave-particle duality to all of nature with his matter-wave equation, $\lambda = \frac{h}{mv}$, where λ is the particle's wavelength, m is its mass, v is its velocity, and h is Planck's constant.

34 Using this equation, calculate the de Broglie wavelength of a helium nucleus (mass = 6.7×10^{-27} kg) moving with a speed of 2.0×10^6 meters per second. [2]

35 The wavelength of this particle is of the same order of magnitude as which type of electromagnetic radiation? [1]

Base your answers to questions 36 through 38 on the following information.

According to Bohr's model of the hydrogen atom, the electron can exist only in certain allowed orbits each having radius r_n, which is determined by the energy level n. The equation for calculating this radius is $r_n = \frac{n^2h^2}{4\pi^2 m_e k e^2}$ where the quantities are represented by the same symbols as in the *Reference Tables for Physical Setting/Physics*.

36 Calculate the radius in meters of the hydrogen atom in the ground state. [3]

37 Express the radius of the hydrogen atom in the ground state in nanometers to the proper number of significant digits. [1]

38 Express, in lowest terms, the ratio of the radius of a hydrogen atom in excited state $n = 4$ to the radius of a hydrogen atom in excited state $n = 2$. [1]

Base your answers to questions 39 through 42 on the following statement.

Under certain conditions an electron and a positron can annihilate each other and produce two photons. Annihilation is a process in which a particle and its antiparticle are converted into energy.

39 Calculate the combined energy in joules of the photons created when an electron and a positron annihilate each other. [2]

40 Assuming the photons are identical, express the energy of one photon in electronvolts. [1]

41 Assuming the photons are identical, calculate the frequency of one photon. [2]

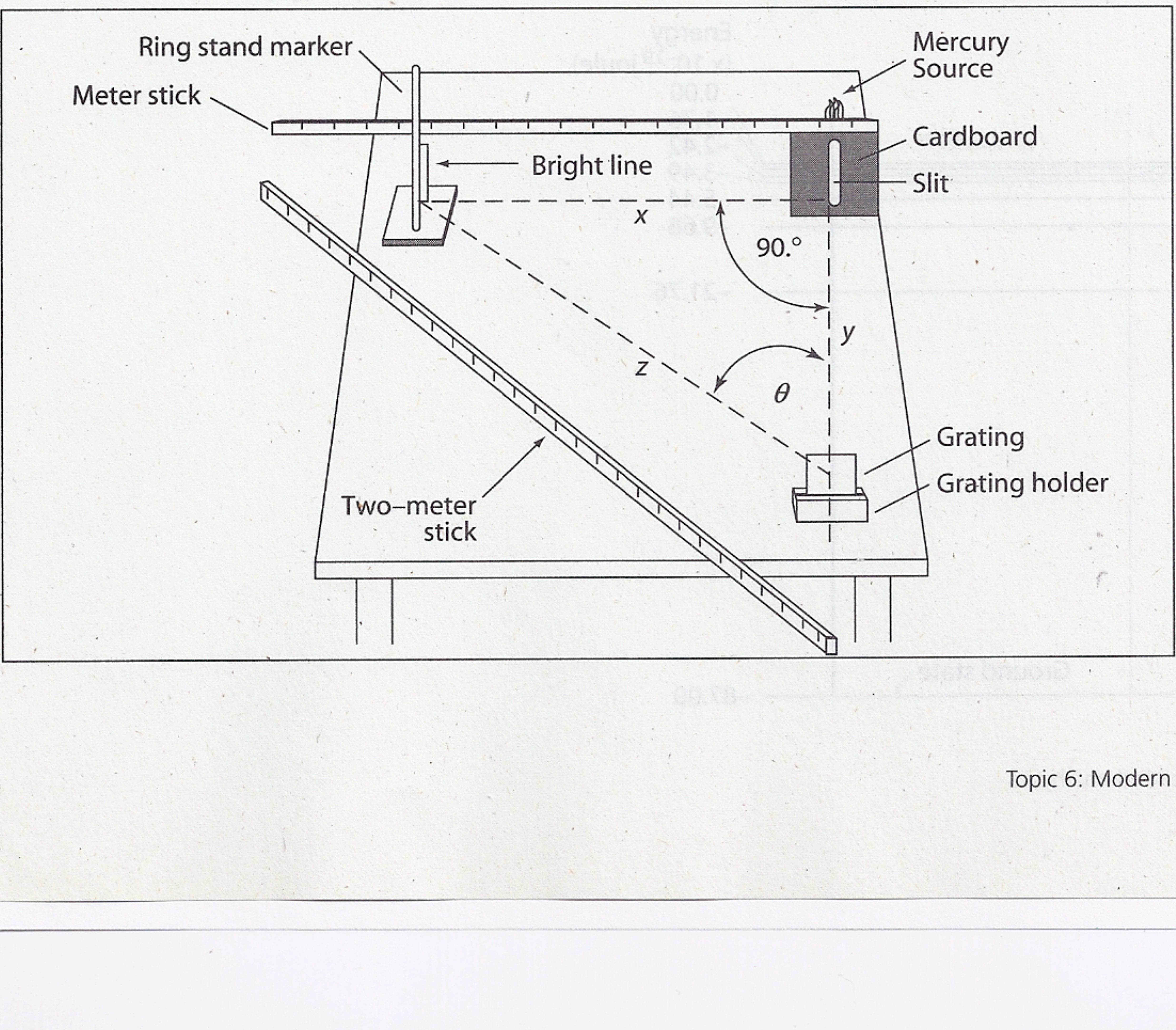
42 According to information in the electromagnetic spectrum chart in the *Reference Tables for Physical Setting/Physics*, how would one of these photons be classified? [1]

Base your answers to questions 43 through 50 on the following information and diagram.

A student performed an experiment using a diffraction grating to measure the wavelengths of the bright lines in mercury's spectrum. A diffraction grating is a device consisting of numerous parallel lines ruled on a glass plate. The device causes light that passes through it from a source to act as individual sources. Where the light interferes constructively, bright lines are produced.

The apparatus used in the experiment included a mercury vapor lamp, exposed by only a thin vertical slit, placed at one corner of a lab table, and a diffraction grating positioned at an adjacent corner. A meter stick was placed at right angles to the line joining the slit and the center of the grating. The rod of a ring stand was used as a guide to mark the distance x of the bright line observed by the student when looking through the grating from the source, as shown. A two-meter stick was used to measure the distance z from the grating to the location of the bright line.

The student was told that the equation $\lambda = d\sin\theta$ could be used to determine the wavelength of the bright line. In the equation, d is the distance between the lines on the glass diffraction grating and θ is the angle between the line joining the source and grating and the line joining the bright line and the grating.



The student was given the value of d. She measured x and z three times and recorded the average x and z, as shown below.

$$d = 1.67 \times 10^{-4} \text{ cm}$$
$$x = 50.4 \text{ cm}$$
$$z = 193.9 \text{ cm}$$

43 Express d in meters. [1]

44 Write an expression that represents the sine of angle θ. [1]

45 Calculate the wavelength of the bright line. [2]

46 According to *the Handbook of Chemistry and Physics*, the accepted value for the wavelength of this line is 4358.33 Å (angstrom units). If 1 Å = 10^{-10} m, what is the accepted value for the wavelength in meters? [1]

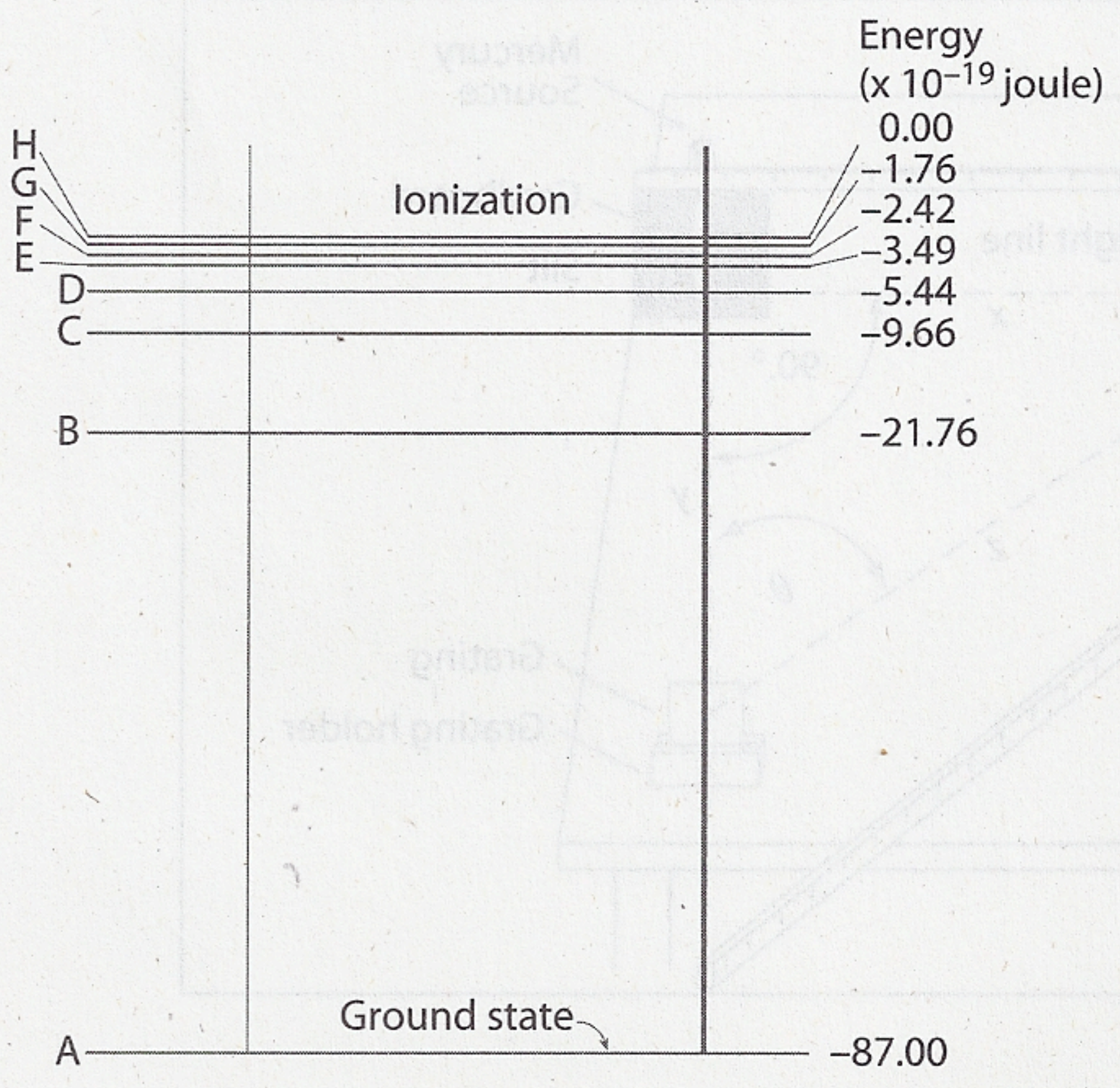
47 Calculate the student's percent error for this bright line measurement. [2]

48 Calculate the energy in joules associated with the student's measured wavelength. [2]

49 Express the energy of the measured line in electronvolts. [1]

50 Refer to the energy level diagram for mercury in the *Reference Tables for Physical Setting/Physics*. Which electron transition is most likely to be the one that the student measured? [1]

Base your answers to questions 51 and 52 on the diagram below, which shows some energy levels for an atom of an unknown substance.



51 Determine the minimum energy necessary for an electron to change from the B energy level to the F energy level. [1]

52 Calculate the frequency of the photon emitted when an electron in this atom changes from the F energy level to the B energy level. [2]

Base your answers to questions 53 and 54 on the information and data table below.

In the first nuclear reaction using a particle accelerator, accelerated protons bombarded lithium atoms, producing alpha particles and energy. The energy resulted from the conversion of mass into energy. The reaction can be written as shown below.

$${}^{1}_{1}\text{H} + {}^{7}_{3}\text{Li} \rightarrow {}^{4}_{2}\text{He} + {}^{4}_{2}\text{He} + \text{energy}$$

Data Table		
Particle	**Symbol**	**Mass (u)**
proton	${}^{1}_{1}\text{H}$	1.007 83
lithium atom	${}^{7}_{3}\text{Li}$	7.016 00
alpha particle	${}^{4}_{2}\text{He}$	4.002 60

53 Determine the difference between the total mass of a proton plus a lithium atom, ${}^{1}_{1}\text{H} + {}^{7}_{3}\text{Li}$, and the total mass of two alpha particles, ${}^{4}_{2}\text{He} + {}^{4}_{2}\text{He}$, in universal mass units. [1]

54 Determine the energy in megaelectronvolts produced in the reaction of a proton with a lithium atom. [1]