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E.1 Structure of the Atom

Understandings

- The Geiger-Marsden-Rutherford experiment and the discovery of the nucleus.
- Nuclear notation ${}^{A}_{Z}X$ where A is the nucleon number, Z is the proton number, and X is the chemical symbol.
- Emission and absorption spectra provide evidence for discrete atomic energy levels.
- Photons are emitted and absorbed during atomic transitions.
- The frequency of the photon released during an atomic transition depends of the difference in energy level as given by $E = hf$.
- Emission and absorption spectra provide information on the chemical composition.

Equations

$E = hf$

Additional HL Understandings

- The relationship between the radius and nucleon number for a nucleus as given by $R = R_0 A^{1/3}$ and implications for nuclear densities.
- Deviations from Rutherford scattering at high energies.
- The distance of closest approach in head-on scattering experiments.
- The discrete energy levels in the Bohr model for hydrogen as given by $E = -\frac{13.6}{n^2}$ eV.
- The existence of quantized energy and orbits arise from the quantization of angular momentum in the Bohr model for hydrogen as given by $mvr = \frac{nh}{2\pi}$.

Additional HL Equations

$R = R_0 A^{1/3}$

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

$mvr = \frac{nh}{2\pi}$

The solutions can be found on the YouTube channel Go Physics Go:

https://www.youtube.com/@gophysicsgo/playlists

Use your favorite sources to answer the following questions

1. C: Draw and describe the main points of the *Thomson model of the atom*:

2. C: Describe the Geiger-Marsden-Rutherford experiment. Draw an image if you have to.

3. C: True or false: Your brain is mostly empty space.

4. C: Describe and draw the *Rutherford model of the atom*:

5. C: Which year were the following particles discovered?

Electron	Photon	Atomic Nucleus
Neutrino	Proton	Neutron

6. C: Define *nucleon number A.*

7. C: Define *atomic number Z.*

8. C: Define *nucleon.*

9. C: Define *nuclide.*

10. C: Define *discrete* and *continuous.*

11. C: Circle the correct answers in italic font: Free electrons have *continuous/ discrete* energy. Bound electrons in an atom have *continuous/discrete* energy.

12. C: Define *ground state* and *excited state* of an electron in an atom. Draw a figure.

13.C: Define *transition.*

14.C: Which has more energy: an electron in an atom which is close to its nucleus or an electron in an atom which is farther from its nucleus? Draw a figure.

15.C: Define *absorption spectra*. What happens to an electron in an atom during *photon absorption*? Draw a figure.

16.C: Define *emission spectrum*. What happens to an electron in an atom during *photon emission*? Draw a figure.

17.C: We use the equation $E = hf$ for *electromagnetic waves*. Define and give the units of each variable.

Additional HL Content

18.C: Give the meaning of the equation $R = R_0 A^{1/3}$ and define each variable.

19.E: Determine the radius of a silver nucleus. Silver has an atomic mass of 108.

20.E: Determine the radius of a gold nucleus. Gold has an atomic mass of 197.

21.C: What is the meaning of *nuclear density*? What is the value of the *nuclear density*?

22.C: Use Newton's second law of motion, the equation for total energy, the equation for angular momentum $\vec{L} = r \times \vec{p}$, and the assumption that the angular momentum of an electron orbiting a hydrogen atom is quantized: $mvr = n\left(\frac{h}{2\pi}\right)$ to derive the equation for the energy of an electron orbiting a hydrogen atom is $E_{\text{electron}} \approx -\frac{13.6}{n^2}$ eV.

23.C: What is the meaning of the equation $E = \frac{-13.6}{n^2}$ eV?

24.E: Determine the radius of the three lowest energy levels of an electron in a hydrogen atom.

25.E: Complete the following table for the four lowest energy levels of an electron in a hydrogen atom.

Energy level	n	E(eV)	E(Joules)
Ground state			
First excited state			
Second excited state			
Third excited state			

26.E: Determine the gain in total energy in eV when an electron jumps from the first excited state ($n = 2$) to the fifth excited state ($n = 6$).

27.E: Determine the gain in total energy in eV when an electron jumps from the ground state ($n = 1$) to the third excited state ($n = 4$).

28.C: Describe the *Bohr model of the atom*.

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E.2 Quantum Physics

Additional HL Understandings

- The photoelectric effect as evidence of the particle nature of light.
- Photons of a certain frequency, known as the threshold frequency, are required to release photoelectrons from the metal.
- Einstein's explanation using the work function and the maximum kinetic energy of the photoelectrons as given by $E_{\mathrm{max}} = hf - \Phi$ where Φ is the work function of the metal.
- Diffraction of particles as evidence of the wave nature of matter.
- Matter exhibits wave-particle duality.
- The de Broglie wavelength for particles as given by $\lambda = \frac{h}{p}$.
- Compton scattering of light by electrons as additional evidence of the particle nature of light.
- Photons scatter off electrons with increased wavelength.
- The shift in photon wavelength after scattering off an electron as given by $\lambda_{\mathrm{f}} - \lambda_{\mathrm{i}} = \Delta\lambda = \frac{h}{m_{\mathrm{e}}c}(1 - \cos\theta)$.

Additional HL Equations

$$E_{\mathrm{max}} = hf - \Phi$$

$$\lambda = \frac{h}{p}$$

$$\lambda_{\mathrm{f}} - \lambda_{\mathrm{i}} = \Delta\lambda = \frac{h}{m_{\mathrm{e}}c}(1 - \cos\theta)$$

If you are interested in learning more about atomic, quantum, and nuclear physics then please read the book *The Quantum Story: A History in 40 Moments* by Jim Baggott.

Also watch all the videos in this website:
https://www.learner.org/series/physics-for-the-21st-century/

The solutions can be found on the YouTube channel Go Physics Go:

https://www.youtube.com/@gophysicsgo/playlists

Use your favorite sources to answer the following questions

1. C: Briefly describe the *photoelectric effect.*

2. C: About how long does it take for the electrons to leave the metal during the photoelectric effect?

3. C: Define *critical/threshold frequency*.

4. C: What will happen to the metal if the intensity of the electromagnetic wave is increased while it is still below the *critical/threshold frequency*? Will the photoelectric effect occur?

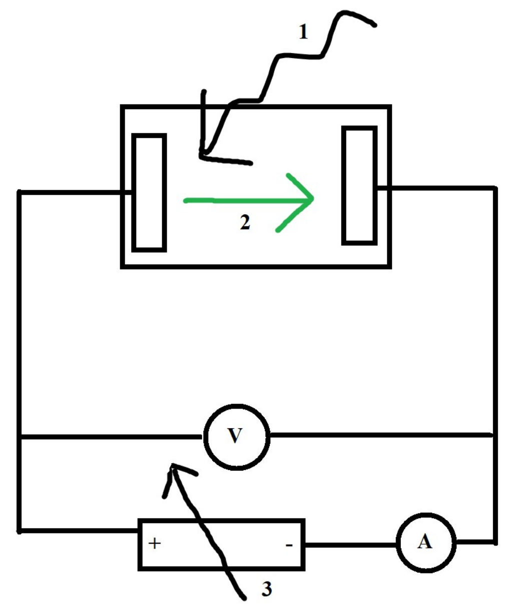
5. C: What will happen to the electrons if the intensity of the electromagnetic wave is increased while it is above the *critical/threshold frequency*?

6. C: What is the *work function* φ?

7. C: Describe the equation given in the IB physics data booklet: $E_{\text{max}} = hf - \varphi$.

8. C: Draw an E_{max} vs. incoming frequency graph for three metals. What does the horizontal and vertical intercepts tell us? What does the slope tell us?

9. C: Describe, step by step, what is happening in the lab setup below.

	Step 1: Step 2: Step 3:

10.C: Define *stopping potential/voltage*.

11. C: From the lab setup from question 9 draw a graph of the *current vs. potential difference across the anode and cathode* with the same incoming frequencies and different intensities.

12. C: From the lab setup from question 9 draw a graph of the *current vs. potential difference across the anode and cathode* with different incoming frequencies.

13. C: What is the meaning of *energy is quantized*?

14. C: For the photoelectric effect draw a *current vs. frequency* graph below the threshold frequency and above the threshold frequency with a constant intensity (incoming photons per second) of incoming photons.

15.C: For the photoelectric effect draw two graphs: a *current vs. intensity* graph below the threshold frequency and a *current vs. intensity* graph above the threshold frequency.

16.E: What is the energy content in Joules of a light wave which has a wavelength of 4.40×10^{3} Angstroms?

17.E: What will be the energy content in Joules of a light wave which has a frequency of 5.25×10^{14} Hz?

18.E: A light wave has an energy content of 2.93×10^{-19} Joules. What will be the wavelength and frequency of this light wave?

19.E: A photoelectric experiment is performed and data is collected as shown below:

Wavelength (Angstroms)	Stopping Potential (Volts)
4425	1.45
4975	1.13
6200	0.81
7075	0.56

a. Determine the kinetic energies of the emitted photoelectrons in Joules.

Stopping Potential (Volts)	KE (Joules)
1.45	
1.13	
0.81	
0.56	

b. Determine the frequencies of the incoming light waves.

Wavelength (Angstroms)	Wavelength (meters)	Frequency (Hz)
4425		
4975		
6200		
7075		

c. Plot a graph comparing the energies of the emitted photoelectrons to the frequencies of the incoming photons.

d. From your graph calculate an experimental value for Planck's constant.

e. From your graph determine the cut off frequency for this surface and the resulting work function for this surface.

f. Determine the equation describing the kinetic energies of the emitted photoelectrons as a function of the incoming light photons and the work function φ for the surface.

20.E: Light, which has a wavelength of $890.$ Angstroms, is incident on a photoelectric surface which has a work function (ionization potential) of -13.6 eV.

a. What is the energy content, in Joules, of this incoming light wave?

b. How much energy, in Joules, would be required to free the least strongly bound electron from this surface?

c. What will be the kinetic energy of the emitted photoelectrons?

d. What will be the velocity of the emitted photoelectrons?

21.E: Light, which has a wavelength of 3.70×10^3 Angstroms, is used to illuminate a photoelectric surface. As a result of this illumination photoelectrons are emitted from the surface. A stopping potential of 1.25 Volts is required to reduce the photocurrent to zero.

a. What is the maximum kinetic energy of the emitted photoelectrons?

b. What is the energy content of the incoming photons?

c. What is the work function of this surface in eV?

22.C: What is the de *Broglie hypothesis*? What is the equation?

23.E: Usain Bolt has a mass of 94.0 kg. He is running with a speed of 10.44 m/s. What is his wavelength?

24.E: An electron, which has a mass of 9.11×10^{-31} kg, is traveling with a speed of 10.44 m/s. What is its wavelength?

25.C: Where can we see particles, such as electrons, diffract? In which experiment do electrons diffract?

26.C: What is the meaning of *wave-particle duality*?

27.C: Describe the *Compton effect*.

28.E: An incoming photon with a wavelength of 6.00×10^{-10} m strikes an electron at rest. The photon rebounds at an angle of 120. degrees to its original direction. Determine the speed and wavelength of the photon after the collision.

29.C: State ***two*** experiments in which light behaves as a wave. Do not explain the experiments, just state them.

30.C: State ***two*** experiments in which light behaves as a particle. Do not explain the experiments, just state them.

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E.3 Radioactive Decay

Understandings

- Isotopes.
- Nuclear binding energy and mass defect.
- The variation of the binding energy per nucleon with nucleon number.
- The mass-energy equivalence as given by $E = mc^2$ in nuclear reactions.
- The existence of the strong nuclear force, a short-range, attractive force between nucleons.
- The random and spontaneous nature of radioactive decay.
- The changes in the state of the nucleus following alpha, beta, and gamma radioactive decay.
- The radioactive decay equations involving α, β^-, β^+, and γ.
- The existence of neutrinos ν and antineutrinos $\bar{\nu}$.
- The penetration and ionizing ability of alpha particles, beta particles, and gamma rays.
- The activity, count rate, and half-life in radioactive decay.
- The changes in activity and count rate during radioactive decay using integral values of half-life.
- The effect of background radiation of count rate.

Equations

$E = mc^2$

$\lambda = \frac{hc}{E}$

Additional HL Understandings

- The evidence for the strong nuclear force.
- The role of the ratio of neutrons to protons for the stability of nuclides.
- The approximate constancy of binding energy curve above a nucleon number of 60.
- The spectrum of alpha and gamma radiations provides evidence for discrete nuclear energy levels.
- The continuous spectrum of beta decay as evidence for the neutrino.
- The decay constant λ and the radioactive decay law as given by $N = N_0 e^{-\lambda t}$.
- The decay constant approximates the probability of decay in unit time only in the limit of sufficiently small λt.
- The activity as the rate of decay as given by $A = \lambda N = \lambda N_0 e^{-\lambda t}$.
- The relationship between half-life and the decay constant as given by $T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$.

Additional HL Equations

$$N = N_0 e^{-\lambda t}$$

$$A = \lambda N = \lambda N_0 e^{-\lambda t}$$

$$T_{\frac{1}{2}} = \frac{\ln}{\lambda}$$

The Evil Revealed in First US Nuclear Test: 74 Years Ago Over Bikini
https://www.activistpost.com/2020/06/the-evil-revealed-in-first-us-nuclear-test-74-years-ago-over-bikini.html

MIT Scientists: Nuclear Fusion Energy Could Be Closer Than Thought
https://oilprice.com/Alternative-Energy/Nuclear-Power/MIT-Scientists-Nuclear-Fusion-Energy-Could-Be-Closer-Than-Thought.html

The solutions can be found on the YouTube channel Go Physics Go:

https://www.youtube.com/@gophysicsgo/playlists

Use your favorite sources to answer the following questions

1. C: Define *isotope.*

2. C: *Isotopes* have the same ___________ properties but different ___________ properties.

3. C: Define *mass defect*. Units?

4. C: Which has more mass: two individual protons or two protons in the same nucleus?

5. C: Define *binding energy*. Units?

6. C: **Use a pencil and ruler!** Draw and label the *binding energy curve*. Label the horizontal and vertical axis. Label the most stable element.

7. C: Define *atomic mass unit*. Units?

8. C: Use the equation $\Delta E = \Delta m \times c^2$ to find the energy equivalent of 1 u in Joules and $\frac{\text{MeV}}{\text{c}^2}$.

9. E: Determine the binding energy per nucleon for a neutral carbon nucleus.

10.C: Define *transmutation.*

11.E: Consider an atom of $^{17}_{37}\mathrm{Cl}$.

a. Determine the number of protons, neutrons, and electrons that make up this atom.

b. Determine the total mass of a Cl-37 nucleus based on the sum of its separate parts in kg and u.

c. The atomic mass of Cl-37 is approximately 36.965903 u. Subtract the mass of the electrons to determine the mass of a Cl-37 nucleus. Convert this to kg.

d. Find the difference between the mass of a single nucleus of Cl-37 and the sum of its parts in both kg and u. This is called the *mass defect*.

e. Convert this “mass defect” into the energy equivalent through $E = mc^2$.

f. Convert the resulting “energy defect” into binding energy per nucleon in $\frac{\mathrm{MeV}}{\mathrm{nucleon}}$.

12.C: What happens in nuclear decay if the *mass difference* is positive? Is nuclear decay possible?

13.C: What happens in nuclear decay if the *mass difference* is negative? Is nuclear decay possible?

14.C: Describe the *strong nuclear force*.

15.C: Define *random* and *spontaneous.*

16.C: *Radioactive decay* is both ___________ and ___________.

17.C: Define *alpha particle*. What is it made of? Charge?

18.C: What is the difference between an *alpha particle* and a *helium atom*?

19.E: Give two examples of *alpha decay*:

20.C: Define *neutrino*. What is it made of? Charge? Mass?

21.C: Define *anti-neutrino*. What is it made of? Charge? Mass?

22.C: Define *positron*. What is it made of? Charge? Mass?

23.C: Define *beta plus particle*. What is it made of? Charge? Mass?

24.C: What happens to a proton in a decaying nucleus during *beta plus decay*?

25.E: Give two examples of *beta plus decay*:

26.C: Define *beta minus particle*. What is it made of? Charge? Mass?

27.C: What is the difference between a *beta minus particle* and an *electron*?

28.C: What happens to a neutron in a decaying nucleus during *beta minus decay*?

29.E: Give two examples of *beta minus decay*:

30.C: Why was the neutrino postulated?

31.C: What is the charge and mass of an electron? What is the charge and mass of a neutrino ν?

32.C: Define *gamma ray*. What is it made of? Charge? Mass?

33.C: Why is it not correct to use the term *gamma particle*?

34.C: What is happening to an atom during *gamma decay*?

35.E: Give two examples of *gamma decay*: Gamma decay takes an excited and unstable atom and then makes it stable by releasing energy (as an electromagnetic wave) from the nucleus.

36.C: Define *ionization.*

37.C: Which particles have the most *ionizing ability* out of alpha particles, beta particles, and gamma rays?

38.C: Define *to penetrate.*

39.C: Define *penetrating power*. Which object can we use to stop an *alpha particle*? A *beta particle*? A *gamma ray*?

40.C: Define *half-life*. Units?

41.C: Define *activity*. Units? Use a **pencil and ruler!** Draw an activity vs. time graph for a radioactive/unstable element.

42.C: Complete the following sentences:

a. After one half-life the activity of the radioactive sample will decrease to ___________ of the original activity.
b. After two half-lives the activity of the radioactive sample will decrease to ___________ of the original activity.
c. After three half-lives the activity of the radioactive sample will decrease to ___________ of the original activity.
d. After four half-lives the activity of the radioactive sample will decrease to ___________ of the original activity.

43.C: Define *count rate*. Units?

44.C: Define *background radiation.*

Additional HL Content

45.C: Why do stable nuclei have more neutrons than protons?

46.C: What is the ratio of neutrons to protons for stable nuclei?

47.C: Circle the correct answer: Alpha particles leave the nucleus with *continuous/ discrete* energy levels.

48.C: Circle the correct answer: Beta minus particles leave the nucleus with *continuous/discrete* energy levels.

49.C: Circle the correct answer: Beta plus particles leave the nucleus with *continuous/discrete* energy levels.

50.C: Circle the correct answer: Gamma rays leave the nucleus with *continuous/ discrete* energy levels.

51.C: What is the meaning and units of the *decay constant* λ?

52.C: Describe and define the variables in the radioactive decay law equation $N(t) = N_0 e^{-\lambda}$.

53.C: What is the meaning and units for *activity A*? Describe and define the variables in the equation $A(t) = \lambda N(t) = \lambda N_0 e^{-\lambda t}$.

54.C: State the relationship between the half-life and the decay constant.

55.E: Cobalt-60 has a half-life of 5.271 years. Suppose that you have a sample of Co-60 which has a mass of 25.0 grams.

a. How many atoms will this sample contain?

b. What is the decay constant for this isotope (in decays per second)?

c. What will be the initial activity of this sample?

d. How many atoms of this sample will remain after 3.00 years?

e. What will be the activity of this sample after 3.00 years?

f. How many grams of radioactive Co-60 will remain after 3.00 years?

56. E: Strontium-90 has a half-life of 28.8 years. Suppose that you have a sample of Sr-90 which has a mass of 45.5 grams.

a. How many atoms will this sample initially contain?

b. What will be the decay constant of this isotope (in decays per second)?

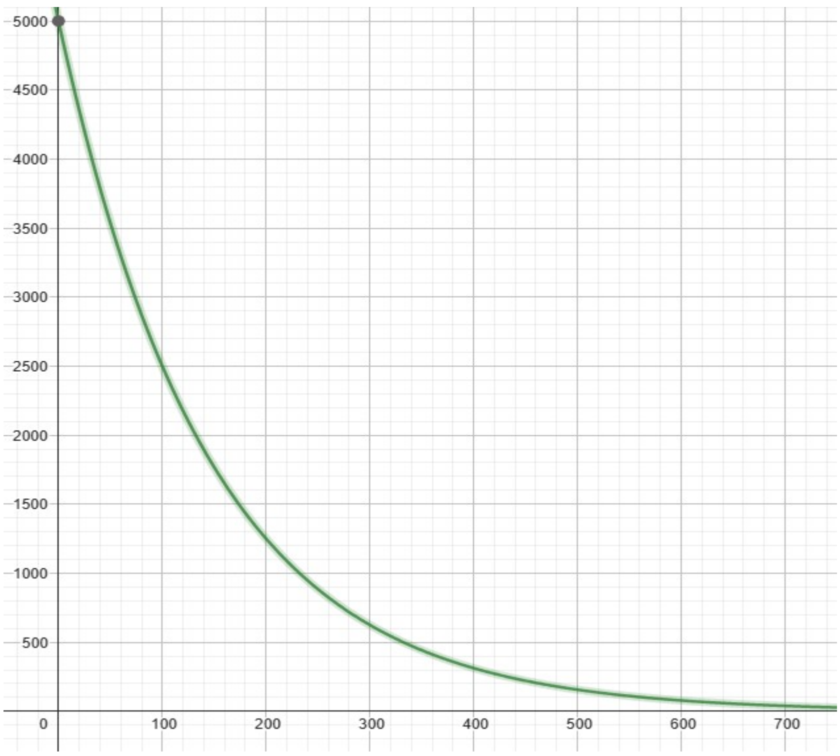
c. What will be the initial activity of this sample?

d. How many radioactive atoms of this isotope will remain after 100. years?

e. What will be the activity of this sample after 100. years?

f. How many grams of Sr-90 will remain after 100. years?

57.E: The graph below plots the activity of a radioactive sample as a function of time.



a. What is the half-life of this radioactive sample?

b. What is the decay constant of this isotope?

c. How many atoms were initially present in this sample?

d. What will be the activity of this sample after 10.0 minutes?

e. How long will it take for the activity of this sample to drop to 1.00% of its initial value?

f. How many radioactive atoms will remain after 10.0 minutes?

g. How many radioactive atoms will have decayed during the first 5.00 minutes?

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E.4 Fission

Understandings

- Energy is released in spontaneous and neutron-induced fission.
- The role of chain reactions in nuclear fission reactions.
- The role of control rods, moderators, heat exchangers, and shielding in a nuclear power plant.
- The properties of the products of nuclear fission and their management.

The solutions can be found on the YouTube channel Go Physics Go:

https://www.youtube.com/@gophysicsgo/playlists

1. C: Define *nuclear fission.*

2. C: Give two examples of *nuclear fission*.

3. C: Define *chain reaction.*

4. C: Define *critical mass*. Units?

5. C: Define *induced process.*

6. C: What are the uses of the following objects in a nuclear reactor?

    a. *control rod*

    b. *moderator*

    c. *heat exchanger*

    d. *fuel rod*

7. C: State two benefits and two drawbacks to using *nuclear power.*

8. E: Below is one example of a fission reaction:

$$ {}^{98}_{252}\mathrm{Cf} \rightarrow {}^{56}_{142}\mathrm{Ba} + {}^{42}_{106}\mathrm{Mo} + 4\,{}^{0}_{1}\mathrm{n} $$

Given the information below determine the change in binding energy to three decimal places.

Total binding energy of Californium-252: 1881.274575 MeV
Total binding energy of Barium-142: 1180.144060 MeV
Total binding energy of Molybdenum-106: 898.95878 MeV
Total binding energy of a neutron: 0 MeV

9. E: A typical fission of one californium-252 nucleus releases about 184.07 MeV of energy. Determine the amount of energy, in Joules, which is released from 10.000 kg of pure californium-252.

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E.5 Fusion and Stars

Understandings

- The stability of stars relies on an equilibrium between outward radiation pressure and inward gravitational forces.
- Fusion is a source of energy in stars.
- The conditions leading to fusion in stars in terms of density and temperature.
- The effect of stellar mass on the evolution of a star.
- The main regions of the Hertzsprung-Russell (HR) diagram and how to describe the main properties of stars in these regions.
- The use of stellar parallax as a method to determine the distance d to celestial bodies as given by $d(\text{parsec}) = \frac{1}{p(\text{arc}-\text{second})}$
- How to determine stellar radii

Equations

$$d(\text{parsec}) = \frac{1}{p(\text{arc}-\text{second})}$$

The solutions can be found on the YouTube channel Go Physics Go:

https://www.youtube.com/@gophysicsgo/playlists

Use your favorite sources to answer the following questions

1. C: Define *nuclear fusion.*

2. C: Give two examples of *nuclear fusion*:

3. C: Define *celestial.*

4. C: Define *star*.

5. C: Define *thermal gas pressure*.

6. C: Define *radiation pressure.*

7. C: Define *gravitational pressure*.

8. C: Define *stellar equilibrium*.

9. C: Define *main sequence star*.

10. C: Define *Sun*.

11. C: Describe the *proton-proton cycle*.

12. C: Define *apparent brightness b.* Units?

13. C: Define *luminosity L.* Units?

14. C: Define a *perfect black body*.

15. C: Describe *Wien's displacement law*.

16.C: Describe the *absorption spectrum*.

17.C: Describe *main sequence stars*.

18.C: Describe the *Hertzsprung-Russell diagram*.

19.C: Describe the *instability strip*.

20.C: Define a *red giant*.

21.C: Define a *red supergiant*.

22.C: Define a *dwarf star*.

23.C: Define *electron degeneracy pressure*.

24.C: Define a *white dwarf*.

25.C: Describe what happens after a *supernova*.

26.C: Describe the term *evolutionary path*.

27.C: Describe the equation $L \propto M^{3.5}$.

28.C: Define *astronomical unit*.

29.C: Define *light year*.

30.C: Define *stellar parallax* (or *parallax method*).

31.C: Define *parallax angle*.

32.C: Define *arc second*.

33.C: Define *parsec*.

34.C: Describe the equation $d(\text{parsec}) = \frac{1}{p(\text{arc-secon }\ )}$.

35.E: An example of a fusion reaction is when deuterium and tritium combine to create helium, a neutron, and energy. Determine the

a. energy released (in MeV) from this reaction with the data given, and

Binding energy of deuterium: 2.22452 MeV
Binding energy of tritium: 8.48179 MeV
Binding energy of helium: 28.2957 MeV
Binding energy of a neutron: 0 MeV

b. the change in mass (in u) from this reaction.

36.E: The temperature of a main sequence star is approximately 2.50×10^4 K.

a. Determine the peak wavelength of this main sequence star.

b. Determine an approximate value of the luminosity of this main sequence star.

c. Determine an approximate value for its radius.

37.E: The surface temperature of a main sequence star is approximately 1.00×10^4 K.

a. Use the Hertzsprung-Russell diagram to estimate the luminosity of the star.

b. The apparent brightness of this main sequence star is approximately $1.60 \times 10^{-9}\ \frac{\mathrm{W}}{\mathrm{m}^2}$. Determine the approximate distance between this main sequence star and Earth.

38.E: The parallax angle to a star is 0.320 arc-seconds. Determine the distance, in meters, to the star.

39.E: The parallax angle for Betelgeuse is approximately 5.95×10^{-3} arc $-$ seconds. Determine the distance of Betelgeuse from Earth in

a. parsecs,

b. meters,

c. light years, and

d. astronomical units.