Gen. Phys. II **Exam 5 - Chs. 29,30 - Photons & Matter Waves, Atomic Physics** **Apr. 26, 2021**

Rec. Time **Name**

For full credit, make your work clear. Show formulas used, essential steps, and results with correct units and significant figures. Points shown in parenthesis. For TF and MC, choose the *best* answer.

OpenStax Ch. 29 - Photons & Matter Waves

1. (4) An electron, a proton, and a bacterium all have the same de Broglie wavelength λ as they travel along. Which one has the highest momentum?

a. The bacterium.. b. The proton. c. The electron.
d. They all have the same momentum.

2. (4) In the experiments on the photo-electric effect performed by R.A. Millikan and analyzed by Albert Einstein, each electron ejected from the metal illuminated with light is produced by

a. just one photon.
b. many photons, with different frequencies.
c. many photons, all with the same frequency.
d. just enough photons to surpass the work function energy.

3. (4) A metal used in a photo-electric experiment is producing no photo-electrons when illuminated with 10.0 W/m^2 of light at 540 nm wavelength. What can be done to start the emission of photo-electrons?

a. decrease the wavelength of the light.
b. increase the wavelength of the light.
c. increase the intensity of the light.
d. decrease the frequency of the light.

4. (6) You know that photons are the quanta of electromagnetic radiation. Sort the types of photons according to *increasing* momentum.

a. blue light b. gamma-rays c. ultraviolet light d. radio waves e. infrared light.

5. (6) A certain metal only produces photo-electrons using light with wavelength $\lambda < 538$ nm. When illuminated with light of wavelength 414 nm, what is the maximum kinetic energy of the photo-electrons, in electron-volts?

6. (6) The spectrum of blackbody radiation from inside a furnace used to smelt metals peaks at the wavelength of 0.981 μm. What is the temperature inside the furnace, in kelvin?

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7. (10) This is the problem for which you must upload your work. You do not need to use relativity here.

An electron is cruising happily along in the electron beam of a cathode ray tube, with a de Broglie wavelength of 0.514 nm (nanometers). Suddenly the electron is stopped by crashing into a metal block, converting all of its kinetic energy into a single photon. Calculate the wavelength of that photon, in nanometers.

1. (3) There is a beautiful green beam observed flowing between the negatively charged cathode and the positively charged anode of a cathode ray tube, invented in 1897 by Karl F. Braun. Cathode rays are now known to be a beam of

a. hydrogen atoms. b. protons. c. neutrons. d. electrons. e. helium ions.

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2. (6) In the quantum theory of atoms, a sub-shell is a limited set of states for electrons. Match the sub-shell with the maximum number of electrons it can hold. [answer choices are 1, 2, 3, 5, 6, 10, or 0 (the subshell does not exist)].

3s ______ 3p ______ 3d ______ 3f ______

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3. (4) Which of these outermost sub-shell configurations would correspond to an element that wants to grab one electron from some other atom? Check all that apply.

a. $2p^5$. b. $5p^6$. c. $5p^5$. d. $3d^{10}$. e. $3p^1$.

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4. (4) An atomic electron is in a state with $n = 2$. What is the largest value that the z-component of its orbital angular momentum can have (along some chosen z-axis)?

a. 0. b. $h/2\pi$. c. $2(h/2\pi)$. d. $3(h/2\pi)$. e. $\sqrt{2}(h/2\pi)$.

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5. (3) In the Zeeman effect, the 4d sub-shell is split into how many different energy levels when a magnetic field is applied to atoms?

a. 2. b. 3. c. 5. d. 6. e. 10.

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6. (6) A hydrogen atom makes a quantum transition from the $n = 8$ state to the $n = 3$ state. According to Bohr's model for the spectrum of light from atoms, what wavelength of light, in nm, is being emitted in the transition?

7. (6) Some atoms have energy levels at $E_1 = -5.00$ eV, $E_2 = -4.50$ eV, and $E_3 = -3.50$ eV. Suppose that there initially are some atoms in each of these three stationary states, and when the energy reaches $E = 0$ eV, the atom is ionized.

a) The longest wavelength of light that the atoms can absorb without being ionized is [248 nm, 354 nm, 827 nm, 1240 nm, 2480 nm]?

b) The shortest wavelength of light that the atoms can absorb without being ionized is [248 nm, 354 nm, 827 nm, 1240 nm, 2480 nm]?

c) The longest wavelength of light that will ionize some of the atoms is [248 nm, 354 nm, 827 nm, 1240 nm, 2480 nm]?

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8. (8) This is the question for which you must show your work in the file upload.
A hydrogen atom initially in its $n = 3$ state absorbs a photon of wavelength 203.1 nm, which is enough to ionize it, leaving the electron with kinetic energy as it is freed from the nucleus. How much kinetic energy in eV does the ejected electron have?

Ch. 27 = __________/40 Ch. 28 = __________/40

Prefixes

a=10^{-18}, f=10^{-15}, p=10^{-12}, n=10^{-9}, $\mu = 10^{-6}$, m=10^{-3}, c=10^{-2}, k=10^{3}, M=10^{6}, G=10^{9}, T=10^{12}, P=10^{15}

Physical Constants

$k = 1/4\pi\epsilon_0 = 8.988$ GNm^2/C^2 (Coulomb's Law)
$e = 1.602 \times 10^{-19}$ C (proton charge)
$m_e = 9.109 \times 10^{-31}$ kg (electron mass)
$c = 3.00 \times 10^8$ m/s (speed of light)
$h = 6.62607 \times 10^{-34}$ J·s (Planck's constant)
$\sigma = 5.67 \times 10^{-8}$ W/(m^2·K^4) (Stefan-Boltzmann const.)
$\epsilon_0 = 1/4\pi k = 8.854$ pF/m (permittivity of space)
$\mu_0 = 4\pi \times 10^{-7}$ T·m/A (permeability of space)
$m_p = 1.67 \times 10^{-27}$ kg (proton mass)
$c = 2.99792458 \times 10^8$ m/s (exact value in vacuum)
$\hbar = 1.05457 \times 10^{-34}$ J·s (Planck's constant/2π)
hc =1239.84 eV·nm (photon energy constant)

Units

$N_A = 6.02 \times 10^{23}$/mole (Avogadro's #)
1.0 eV = 1.602×10^{-19} J (electron-volt)
1 F = 1 C/V = 1 farad = 1 C^2/J
1 A = 1 C/s = 1 ampere = 1 coulomb/second
1 T = 1 N/A·m = 1 tesla = 1 newton/ampere·meter
1 u = 1 g/N_A = 1.6605×10^{-27} kg (mass unit)
1 V = 1 J/C = 1 volt = 1 joule/coulomb
1 H = 1 V·s/A = 1 henry = 1 J/A^2
1 Ω = 1 V/A = 1 ohm = 1 J·s/C^2
1 G = 10^{-4} T = 1 gauss = 10^{-4} tesla

OpenStax Chapter 24 Equations - Electromagnetic Waves

Electromagnetic waves:

$|\vec{E}|/|\vec{B}| = c = 1/\sqrt{\epsilon_0\mu_0}$, (fields and speed)
$f\lambda = c$ (wave equation)

Energy density, intensity, power:

$u = \epsilon_0 E^2 = \frac{B^2}{\mu_0}$ (instantaneous energy density)
$\overline{u} = \frac{1}{2}\epsilon_0 E_0^2 = \frac{B_0^2}{2\mu_0}$ (average energy density)
$I = \overline{u}c = \frac{1}{2}\epsilon_0 E_0^2 c$ (EM waves intensity)
$I = P/A = P/(4\pi r^2)$ (intensity definition)

Approximate wavelengths λ for types of EM waves:

0 (γ-rays) 30 pm (x-rays) 3 nm (uv) 400 nm (visible) 700 nm (ir) 300 μm (μ-waves) 3 cm (radio) ∞

$\longrightarrow$ $\longrightarrow$ $\longrightarrow$ increasing wavelength $\longrightarrow$ $\longrightarrow$ $\longrightarrow$

OpenStax Chapter 28 Equations - Special Relativity

Time dilation and length contraction:

$\Delta t = \gamma\Delta t_0 = \Delta t_0/\sqrt{1 - v^2/c^2}$
$\gamma = 1/\sqrt{1 - v^2/c^2}$ (relativistic factor)
$L = L_0/\gamma = L_0\sqrt{1 - v^2/c^2}$
$v/c = \sqrt{1 - 1/\gamma^2}$ (velocity)

Dyanmics, mass, energy:

$p = \gamma mv$ (relativistic momentum)
$E_0 = mc^2$ (rest energy)
$\mathrm{KE} = E - E_0 = (\gamma - 1)mc^2$ (kinetic energy)
$\Delta(E_0 + \mathrm{KE}) + \Delta\mathrm{PE} = 0$ (conservation of energy)
$m_{\mathrm{rel}} = \gamma m$ (relativistic mass)
$E = \gamma mc^2 = m_{\mathrm{rel}}c^2$ (relativistic energy)
$E = E_0 + \mathrm{KE} = \sqrt{p^2c^2 + m^2c^4}$ (relativistic energy)
$\Delta\mathrm{PE}_{\mathrm{elec}} = q\Delta V$ (electric potential energy)

OpenStax Chapter 29 Equations - Quanta and Quantum Waves

Blackbody radiation, photons, photo-electric effect:

$\lambda_p T = 2.90$ mm·K (Wien's Law) | $I = \sigma T^4$ (intensity or power/area)

$E = nhf,\ n = 1, 2, 3...$ (quantized radiation energy) | $E = hc/\lambda = (1240 \text{ eV} \cdot \text{nm})/\lambda$ (photons)

$E = hf = W_0 + \text{KE}_{\text{max}}$ (photo-electrons) | $hc/\lambda_{\text{max}} = W_0$ (work function)

$\text{KE}_{\text{max}} = eV_0$ (stopping potential) | $v_{\text{max}} = \sqrt{2\text{KE}_{\text{max}}/m}$ (max. speed)

Momentum, matter waves:

$p = h/\lambda$ (quantum momentum) | $\lambda' = \lambda + \frac{h}{mc}(1 - \cos\phi)$ (Compton effect)

$\lambda = h/p$ (de Broglie wavelength) | KE$= p^2/2m$ (kinetic energy, $v \ll c$)

$\Delta\text{KE}+q\Delta V = 0$ (acceleration thru potential) | $v = \sqrt{2q\Delta V/m}$ (acceleration thru potential, $v \ll c$)

Heisenberg Uncertainty Principle:

$\Delta x\ \Delta p_x \approx h$ (approximate relation) | $h = 6.626 \times 10^{-34}$ J·s

$\Delta E\ \Delta t \approx h$ (approximate relation)

$\Delta x\ \Delta p_x \geq \hbar/2$ (has the minimum uncertainty) | $\hbar = \frac{h}{2\pi} = 1.05459 \times 10^{-34}$ J·s

$\Delta E\ \Delta t \geq \hbar/2$ (energy-time form)

$\Delta E = \Delta m \cdot c^2$ (Einstein's mass-energy equivalence) | $\leftarrow$ This has exact equality.

OpenStax Chapter 30 Equations - Atomic Physics

Bohr Model:

$hf = E_n - E_{n'}$ (quantum jump) | $L = mvr = n\frac{h}{2\pi}$ (Bohr's quantization)

$r_n = \frac{n^2}{Z} r_1$ (Bohr radii) | $r_1 = \frac{h^2}{4\pi^2 mke^2} = 52.9$ pm (1st Bohr radius)

$E_n = -(13.6 \text{ eV})\frac{Z^2}{n^2}$ (Bohr energies) | $E_n = \frac{1}{2}mv^2 - \frac{kZe^2}{r_n}$ (total energy)

$n = 1, 2, 3, ...$ (Bohr's quantum number) | $E = hc/\lambda = (1240 \text{ eV} \cdot \text{nm})/\lambda$ (photons)

Quantum numbers for atoms:

principle quantum number $n = 0, 1, 2, 3...$ | $E_n = -(13.6 \text{ eV})/n^2$ (energy of hydrogen states)

orbital quantum number $l = 0, 1, 2...(n-1)$ | $L = \sqrt{l(l+1)}\ \hbar$ (angular momentum magnitude)

magnetic quantum number $m_l = -l$ to $+l$ | $L_z = m_l\hbar$ (z-component of $\vec{L}$)

spin quantum number $m_s = -\frac{1}{2},\ +\frac{1}{2}$ | $S_z = m_s\hbar$ (z-comp., spin angular momentum)

shell ($2n^2$ states) = a value of (n) is given. | *sub-shell* $[2(2\ell+1)$ states$]$ = values of (n, l) are given.

orbital (2 states) = particular (n, l, m_l) are given. | *state* = particular (n, l, m_l, m_s) are given.

$l = 0, 1, 2, 3, 4, 5, 6...$ are indicated with respective letters: s, p, d, f, g, h,...

Pauli exclusion principle: *No two electrons in an atom can occupy the same quantum state.*

Subshells in order of increasing energy: 1s, 2s, 2p, 3s, 3p, 4s, 3d, 4p, 5s, 4d, 5p, 6s, 4f, 5d, 6p, 7s, 5f, 6d, 7p

(They fill in order of increasing $n + l$, but higher n is higher energy if there is a tie.)