Question 1: "Attempt all parts of the following question :"

- (a) **Beta** radiation consists of high-energy electrons or positrons.
- (b) **Geiger-Müller counter** (or GM counter) is sensitive to low levels of radiation.
- (c) Electromagnetic waves with high frequency are characteristic of **Gamma** radiation.
- (d) 1 Roentgen = 2.58×10^{-4} C/kg.
- (e) The particle that results from the electron-positron annihilation process is a **photon** (usually two gamma-ray photons).
- (f) True/False: Semiconductor detectors have greater energy resolution than gas-filled detectors. **True**.

Question 2:

(a) Name the various types of radiation sources.

- **Natural Radiation Sources:**
  - **Cosmic Radiation:** Originates from outer space and interacts with the Earth's atmosphere.
  - **Terrestrial Radiation:** Emitted from naturally occurring radioactive materials (e.g., uranium, thorium, potassium-40) in the Earth's crust, soil, and building materials.
  - **Internal Radiation:** From radionuclides naturally present within the human body (e.g., potassium-40, carbon-14).
  - **Radon Gas:** A naturally occurring radioactive gas produced from the decay of uranium in soil and rocks, which can accumulate in buildings.
- **Artificial (Man-made) Radiation Sources:**
  - **Medical Sources:**

    - Diagnostic X-rays (e.g., radiographs, CT scans, mammography).
    - Nuclear Medicine (e.g., radioisotopes used for imaging and therapy like PET scans, thyroid treatments).
    - Radiation Therapy (e.g., linear accelerators for cancer treatment).
  - **Industrial Sources:**
    - Industrial radiography (for non-destructive testing).
    - Gauges and detectors (e.g., smoke detectors with americium-241, level gauges).
    - Sterilization of medical equipment and food products.
  - **Consumer Products:**
    - Certain luminous dials and smoke detectors (though less common now).
  - **Nuclear Facilities:**
    - Nuclear power plants (controlled release of radioactive materials during operation and waste).
    - Nuclear weapons testing (fallout from historical tests).
  - **Research and Academic Institutions:**
    - Laboratories using radioisotopes for various scientific experiments.

(b) What are the parameters which govern the interaction of heavy charged particle with matter?

The interaction of heavy charged particles (like protons, alpha particles, and fission fragments) with matter is primarily governed by their electrical interaction with the atomic electrons and nuclei of the absorbing material. The key parameters that influence these interactions are:

- **Charge of the Particle (Z):**
    - The stopping power (energy loss per unit path length) of a charged particle is directly proportional to the square of its charge (Z^2).
    - Higher charge leads to stronger Coulombic interaction and thus greater energy loss and shorter range.
- **Velocity (or Kinetic Energy) of the Particle (v):**
    - The rate of energy loss is inversely proportional to the square of the particle's velocity ($1/v^2$) at lower energies.
    - As the particle slows down, its interaction time with atomic electrons increases, leading to more efficient energy transfer and a peak in energy loss near the end of its range (Bragg peak).
    - At very high energies, relativistic effects become important.
- **Mass of the Particle (M):**
    - While not directly appearing in the basic Bethe-Bloch formula for stopping power, the mass influences the velocity for a given kinetic energy ($KE = 1/2Mv^2$).
    - Heavier particles, for the same kinetic energy, have lower velocities and thus generally have higher stopping powers compared to lighter particles with the same charge.
- **Atomic Number (Z) of the Absorbing Material:**
    - The stopping power of the medium is approximately proportional to the atomic number of the absorbing material.
    - Materials with higher Z have more electrons per atom, leading to more frequent interactions.
- **Atomic Mass (A) of the Absorbing Material:**

- The number density of atoms in the medium, which is related to its density and atomic mass, also influences the interaction rate.
- The mass density of the absorber is crucial in determining the *mass stopping power* (energy loss per unit mass thickness).

- **Ionization Potential (I) of the Absorbing Material:**
  - The mean excitation or ionization potential of the absorbing material, which represents the average energy required to ionize or excite an atom of the material.
  - This parameter accounts for the electronic structure of the absorber and its ability to absorb energy from the incident charged particle.
- **Density of the Absorbing Material (ρ):**
  - A denser material presents more atoms per unit volume, leading to more frequent interactions and higher energy loss per unit path length (linear stopping power).
- **Particle's Trajectory (less significant for heavy charged particles):**
  - Heavy charged particles mostly travel in straight lines due to their large mass, making scattering less pronounced compared to electrons. This simplifies the trajectory parameter.

Question 3:

(a) Calculate the maximum energy of a photoelectron ejected from Al by UV light with a wavelength of 1500 Å?

Given:

- Wavelength of UV light (λ) = 1500 Å = 1500×10^{-10} m = 1.5×10^{-7} m

- Work function of Aluminum (Φ_{Al}) = 4.2 eV (from search)

Constants:

- Planck's constant (h) = 6.626×10^{-34} J s
- Speed of light (c) = 3×10^{8} m/s
- Charge of electron (e) = 1.602×10^{-19} C
- 1 eV = 1.602×10^{-19} J

First, calculate the energy of the incident UV photon (E_{photon}): $E_{photon} = \frac{hc}{\lambda}$ $E_{photon} = \frac{(6.626\times10^{-34}\text{ J s})\times(3\times10^{8}\text{ m/s})}{1.5\times10^{-7}\text{ m}}$ $E_{photon} = \frac{19.878\times10^{-26}}{1.5\times10^{-7}}$ J $E_{photon} = 13.252 \times 10^{-19}$ J

Now, convert the photon energy to electron volts (eV): $E_{photon\,(\text{eV})} = \frac{13.252\times10^{-19}\text{ J}}{1.602\times10^{-19}\text{ J/eV}}$ $E_{photon\,(\text{eV})} \approx 8.272$ eV

Next, calculate the maximum kinetic energy of the ejected photoelectron ($E_{k,max}$) using the photoelectric effect equation: $E_{k,max} = E_{photon} - \Phi_{Al}$ $E_{k,max} = 8.272$ eV $- 4.2$ eV $E_{k,max} = 4.072$ eV

The maximum energy of a photoelectron ejected from Al by UV light with a wavelength of 1500 Å is approximately **4.072 eV**.

(b) How do linear and mass attenuation coefficients play a role in photon interaction with matter?

- **Linear Attenuation Coefficient (μ):**
  - **Definition:** The linear attenuation coefficient (μ) quantifies the fraction of photons removed from a monoenergetic beam per unit thickness of the absorbing material. It has units of inverse length (e.g., cm^{-1} or m^{-1}).
  - **Role in Photon Interaction:**

- It describes the probability of an interaction (absorption or scattering) occurring as a photon passes through a material.
- A higher μ means that the material is more effective at attenuating (reducing the intensity of) the photon beam for a given thickness.
- It is used in the Beer-Lambert law ($I = I_0 e^{-\mu x}$) to calculate the intensity of a photon beam after passing through a thickness (x) of material.
- It depends on the photon energy and the type of material (atomic number and density).

- **Mass Attenuation Coefficient (μ/ρ):**
  - **Definition:** The mass attenuation coefficient (μ/ρ) is the linear attenuation coefficient divided by the density (ρ) of the absorbing material. It has units of area per unit mass (e.g., cm^2/g or m^2/kg).
  - **Role in Photon Interaction:**
    - It removes the dependence on the physical density of the material, making it useful for comparing the attenuating properties of different materials regardless of their physical state (solid, liquid, gas).
    - It represents the attenuating power of a given mass of material. For a specific photon energy, the μ/ρ for a given element is essentially constant, irrespective of its physical or chemical state.
    - It is particularly useful when dealing with compounds or mixtures, where the mass attenuation coefficient of the mixture can be calculated from the weighted sum of the mass attenuation coefficients of its constituent elements.

        - It is fundamental in radiation shielding calculations and dose estimation, as it provides a measure of how effectively different materials absorb or scatter photons on a mass basis.
    - **Relationship:** The linear attenuation coefficient can be obtained by multiplying the mass attenuation coefficient by the density of the material: $\mu = (\mu/\rho) \times \rho$.

In summary, both coefficients are crucial for understanding and predicting how photons interact with matter. The linear coefficient is practical for calculating attenuation over a specific distance, while the mass coefficient provides a density-independent measure of material's attenuating power, essential for comparing materials and for applications where density variations might occur.

Question 4:

(a) Give one reason why semiconductors are preferred over metals and insulators for these devices?

One significant reason why semiconductors are preferred over metals and insulators for radiation detection devices (like solid-state detectors) is their **controllable electrical conductivity** and the **existence of an appropriate band gap**.

- **Metals:**
    - Have no band gap (conduction band overlaps valence band).
    - Electrons are freely available, making it difficult to detect small amounts of charge generated by radiation, as the intrinsic noise level is very high. They are good conductors but not good insulators, meaning they cannot sustain an electric field for charge collection effectively without high leakage current.
- **Insulators:**
    - Have a very large band gap (typically > 5 eV).

- A large amount of energy is required to excite electrons from the valence band to the conduction band.
- While they can sustain an electric field, the number of charge carriers created by incident radiation is often too small to be efficiently collected or produce a measurable signal, especially for lower energy depositions, and their charge mobility can be very low.

- **Semiconductors:**
  - Have a moderate and controllable band gap (typically 0.5 to 3 eV, e.g., ~1.12 eV for Si, ~0.7 eV for Ge).
  - This intermediate band gap allows for:
    - **Efficient Charge Carrier Generation:** Incident radiation can easily excite electrons from the valence band to the conduction band, creating electron-hole pairs. The energy required to create an electron-hole pair is much smaller (e.g., ~3.6 eV for Si) than the energy required to create an ion pair in a gas (e.g., ~30 eV). This means more charge carriers are produced per unit of absorbed energy, leading to a larger and more sensitive signal.
    - **Effective Charge Collection:** With proper doping, semiconductors can be engineered to form a depletion region, which acts as an intrinsic electric field. This field efficiently separates and collects the generated electron-hole pairs, leading to a measurable current pulse.
    - **High Energy Resolution:** Because the energy required to produce an electron-hole pair is very consistent and small, semiconductor detectors exhibit excellent energy resolution, allowing for precise determination of the energy of the incident radiation. This is superior to gas-filled detectors where the energy per ion pair is higher and subject to more statistical fluctuations.

(b) Explain the principle and working of scintillation detectors?

- **Principle of Scintillation Detectors:**
  - The fundamental principle of scintillation detection is the conversion of kinetic energy from incident ionizing radiation into detectable light photons (scintillations).
  - Certain materials, called **scintillators**, possess the property of luminescence, meaning they emit light when excited by radiation. This light emission occurs very rapidly after the energy deposition.
  - The intensity of the emitted light is proportional to the energy deposited by the incident radiation.
  - This light is then converted into an electrical signal, typically by a photomultiplier tube (PMT) or a silicon photomultiplier (SiPM).

- **Working of Scintillation Detectors:**

  a. **Interaction of Radiation with Scintillator:**
  - When an ionizing particle (e.g., alpha, beta, gamma, X-ray) enters the scintillator material, it loses energy through various interaction processes (e.g., photoelectric effect, Compton scattering, pair production for photons; ionization and excitation for charged particles).
  - This energy deposition excites the atoms or molecules of the scintillator material.

  b. **Light Emission (Scintillation):**
  - The excited atoms or molecules quickly de-excite, emitting a burst of light photons (scintillations) in the visible or ultraviolet range.
  - The number of photons emitted is proportional to the energy deposited by the incident radiation.

  - Different scintillators have different light output efficiencies and decay times (how quickly they emit light). Common scintillators include Sodium Iodide (NaI(Tl)), Bismuth Germanate (BGO), and plastic scintillators.

c. **Light Collection:**

  - The emitted light photons are collected and guided towards a light-sensitive device, usually a Photomultiplier Tube (PMT).
  - The scintillator crystal is often wrapped in reflective material (e.g., aluminum foil) to maximize light collection and minimize light loss.

d. **Conversion to Electrical Signal (Photomultiplier Tube - PMT):**

  - The PMT consists of several key components:
    - **Photocathode:** When a light photon strikes the photocathode, it ejects an electron via the photoelectric effect.
    - **Dynodes:** These are a series of electrodes (typically 10-14) maintained at progressively higher positive voltages. The ejected electron from the photocathode is accelerated towards the first dynode. When it strikes the dynode, it causes the emission of several secondary electrons (typically 3-6 electrons per incident electron).
    - **Electron Multiplication:** These secondary electrons are then accelerated to the next dynode, where the multiplication process repeats. This cascading effect creates a large avalanche of electrons (a current pulse) from a single initial

photoelectron. The gain of a PMT can be very high, typically 10^5 to 10^7.

- **Anode:** The final dynode collects this amplified pulse of electrons, which is then sent out as an electrical signal.

e. **Signal Processing:**

- The electrical pulse from the PMT anode is proportional to the number of light photons collected, which in turn is proportional to the energy deposited by the incident radiation in the scintillator.
- This pulse is then amplified, shaped, and processed by electronic circuitry (e.g., preamplifier, amplifier, pulse height analyzer) to determine the energy of the radiation and count the number of events.

- **Advantages:** High detection efficiency for gamma rays (especially NaI(Tl)), good energy resolution (better than GM counters, but typically less than semiconductors), and fast response times.
- **Applications:** Widely used in nuclear physics research, medical imaging (PET, SPECT), environmental monitoring, security screening, and geological exploration.

Question 5:

(a) How does annual limit of intake (ALI) limit radiation exposure dose?

The Annual Limit on Intake (ALI) limits radiation exposure dose by setting a maximum amount of a specific radionuclide that a person can take into their body (via inhalation, ingestion, or skin absorption) in a year without exceeding a defined dose limit.

- **Definition:** ALI is the derived limit for the amount of radioactive material taken into the body of an adult worker by inhalation or ingestion in a year that would result in a committed effective dose equal to the annual occupational effective dose limit (e.g., 20 mSv or 50 mSv, depending on regulatory body).

- **Mechanism of Dose Limitation:**
  - **Internal Exposure Control:** ALI specifically addresses **internal radiation exposure**, which occurs when radioactive materials enter the body and irradiate organs and tissues from within. Unlike external exposure, which can be shielded by distance and barriers, internal exposure continues as long as the radionuclide remains in the body.
  - **Committed Dose:** The dose from an intake of radioactive material is not delivered instantaneously. Instead, it is spread over time as the radionuclide decays and is eliminated from the body. ALI accounts for the **committed dose**, which is the total dose accumulated over a 50-year period (for workers) or a 70-year period (for the public) following the intake of a radionuclide.
  - **Radionuclide Specificity:** ALI values are specific to each radionuclide and its chemical form, as different radionuclides have different decay characteristics (half-life, type and energy of radiation emitted) and different metabolic pathways (how they are absorbed, distributed, retained, and eliminated by the body).
  - **Derived Limit:** ALI is a *derived limit*, meaning it is calculated from fundamental dose limits. Regulators set primary dose limits (e.g., effective dose, equivalent dose to organs). ALI then translates these primary dose limits into practical limits on intake amounts.
  - **Preventative Measure:** By ensuring that the intake of radionuclides by workers (or the public) does not exceed the ALI, regulatory bodies aim to prevent individuals from

accumulating an internal radiation dose that would surpass the established annual dose limits, thereby protecting them from adverse health effects.

(b) How is Derived Air Concentration (DAC) used to ensure the safety of workers under radiation environment?

Derived Air Concentration (DAC) is a radiation protection quantity that works in conjunction with ALI to ensure the safety of workers in environments where airborne radioactive materials might be present.

- **Definition:** DAC is the concentration of a given radionuclide in the air (e.g., in Bq/m^3 or μCi/mL) which, if inhaled by a worker for a working year (typically 2000 hours, or 40 hours/week for 50 weeks) at a standard breathing rate, would result in an intake equal to the Annual Limit on Intake (ALI) for that radionuclide.
    - Mathematically: DAC = ALI / (Breathing Rate × Working Hours per year)
- **Ensuring Worker Safety:**
    - **Direct Control of Airborne Contamination:** DAC provides a practical, measurable limit for the concentration of radioactive materials in the air of a workplace. It translates the internal dose limit (ALI) into an actionable air concentration limit.
    - **Workplace Monitoring:** Health physicists and radiation safety officers use DAC values to design and implement air monitoring programs in facilities where radioactive materials are handled. Air samples are collected and analyzed to determine if the airborne concentrations are below the DAC.
    - **Operational Control and Alarm Levels:** DAC helps in establishing operational controls and alarm levels for ventilation systems, personal protective equipment (PPE) requirements (e.g., respirators), and access restrictions. If air concentrations approach or exceed DAC, specific actions (e.g., evacuation,

improved ventilation, respirator use) are triggered to protect workers.

- **Dose Assessment for Internal Exposure:** If a worker is exposed to airborne contamination, the duration of exposure and the measured air concentration can be used to estimate the actual intake and, consequently, the committed internal dose to the worker. This allows for compliance checks against the ALI and overall dose limits.
- **Compliance and Regulatory Enforcement:** Regulatory bodies often stipulate that airborne concentrations of radionuclides in workplaces must not exceed specified DAC values to ensure compliance with radiation safety standards and to prevent unacceptable internal doses to workers.
- **Risk Management:** By providing a clear benchmark for acceptable airborne radioactivity, DAC aids in managing the risk of internal contamination and helps to ensure that worker exposures are kept As Low As Reasonably Achievable (ALARA).

Question 6:

(a) List the basics of radiation hazards evaluation and control.

The basics of radiation hazards evaluation and control are fundamental principles aimed at protecting individuals and the environment from the harmful effects of ionizing radiation. These can be categorized as:

- **Radiation Hazards Evaluation (Assessment):**
  - **Identify Radiation Sources:**
    - Determine the type of radiation (alpha, beta, gamma, neutron, X-ray).
    - Identify the radionuclides involved, their half-lives, and decay schemes.

        - Characterize the physical form (sealed, unsealed, gaseous, liquid) and activity of the sources.
    - **Assess Exposure Pathways:**
        - **External Exposure:** Direct irradiation from outside the body (e.g., gamma rays from a source).
        - **Internal Exposure:** Inhalation, ingestion, or absorption through skin of radioactive materials.
    - **Quantify Radiation Fields:**
        - Measure dose rates (e.g., in μSv/hr or mR/hr) using radiation survey meters.
        - Perform contamination surveys (e.g., swipe tests for removable contamination, direct surveys for fixed contamination).
        - Conduct air sampling for airborne radioactivity.
    - **Estimate Potential Doses:**
        - Calculate potential effective and equivalent doses to workers and the public based on source strength, distance, shielding, and exposure duration.
        - Consider committed doses for internal exposures.
    - **Evaluate Potential Health Effects:**
        - Understand the relationship between dose and potential deterministic (e.g., acute radiation syndrome, burns) and stochastic (e.g., cancer, genetic effects) health effects.
    - **Determine Regulatory Compliance:**
        - Compare estimated doses and measured levels against established regulatory dose limits (e.g., annual dose limits

for workers and the public, derived limits like ALI and DAC).

- **Radiation Hazards Control (Protection):**
  - **ALARA Principle (As Low As Reasonably Achievable):**
    - The overarching principle of radiation protection. It means making every reasonable effort to maintain exposures to radiation as far below the dose limits as is practical, taking into account economic and social factors.
  - **Time, Distance, Shielding (The Three Principles of Radiation Protection):**
    - **Time:** Minimize the duration of exposure. Less time spent in a radiation field means less accumulated dose.
    - **Distance:** Maximize the distance from the radiation source. Radiation intensity decreases rapidly with distance (inverse square law for point sources).
    - **Shielding:** Interpose appropriate shielding material between the source and the person. The type and thickness of shielding depend on the type and energy of the radiation (e.g., lead for gamma, concrete for neutrons, plastic for beta).
  - **Containment and Contamination Control:**
    - **Containment:** Prevent the spread of radioactive material (e.g., using glove boxes, fume hoods, sealed sources, controlled ventilation).
    - **Contamination Monitoring:** Regularly monitor surfaces, skin, and clothing for contamination.
    - **Decontamination:** Procedures for removing radioactive contamination from people, equipment, and areas.

    - **Waste Management:** Proper segregation, storage, and disposal of radioactive waste.
  - **Personnel Monitoring:**
    - **External Dosimetry:** Use personal dosimeters (e.g., TLDs, OSLDs) to measure external radiation dose received by workers.
    - **Internal Dosimetry:** Use bioassay (e.g., urine samples, whole-body counting) to assess and track internal radionuclide intake.
  - **Engineering Controls:**
    - Design of facilities with appropriate shielding, ventilation systems (e.g., negative pressure rooms to prevent outward spread of contamination), and interlocks to prevent accidental exposure.
    - Automated or remote handling equipment to reduce worker proximity to sources.
  - **Administrative Controls:**
    - **Procedures and Work Permits:** Written procedures for handling radioactive materials and conducting radioactive work, often requiring permits.
    - **Training and Education:** Ensuring all personnel working with radiation are adequately trained in radiation safety principles and procedures.
    - **Area Classification and Posting:** Designating and clearly marking radiation areas (e.g., "Radiation Area," "High Radiation Area," "Airborne Radioactivity Area").
    - **Emergency Planning:** Developing and practicing emergency response plans for radiation incidents.

- **Medical Surveillance:**
  - Routine medical examinations for radiation workers, including baseline and periodic health checks, to monitor for any potential health effects.