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A study on interaction of alpha particles with nuclei

Aashi Mittal

Asst. Prof., Dept. of Physics, Hindu Girls College, Sonipat, Haryana, India.

Abstract

Alpha particles react strongly with matter because they are comparatively heavy and have a charge, producing large numbers of ions per unit length of their path. As a result, they are not very penetrating. For example, 5 MeV alpha particles will only travel about 3.6 cm in air and will not penetrate an ordinary piece of paper. For the other materials the average travel distance with respect to air is approximately inversely proportional to the respective densities of each material. 5 MeV alpha particles will only travel about 4 µm in mammal tissue.

Keywords: Alpha particle, Nuclei, Photon energy.

1. Introduction

Alpha particles can interact with either nuclei or orbital electrons in any absorbing medium such as air, water, tissue or metal. An alpha passing in the vicinity of nucleus may be deflected with no change in energy (Rutherford scattering), deflected with small change in energy or absorbed by nucleus, causing nuclear transformation (this process is negligible for alphas).

The most probable process involved in the absorption of alphas, however, are ionization and excitation of orbital electrons. Ionization occurs whenever the alpha particle is sufficiently close to electron to pull it out from orbit though coulomb attraction. Each time this occurs, the alpha loses kinetic energy and is thus slowed.

The alpha also loses kinetic energy by exciting orbital electrons with interactions that are insufficient to cause ionization. As it becomes slowed, the alpha has tendency to cause ionization at an increasing rate. As the alpha nears to the end of its track, its rate of ionization peaks and within very short distance, it stops, collects two electrons and becomes helium atom.

The various processes of photon attenuation can now be considered by examining the effects of photon energy and atomic mass number of the absorber on their relative importance. The lines in the figure indicate the values of the photon energy and Z where the probabilities of occurrence of two major processes are equal.

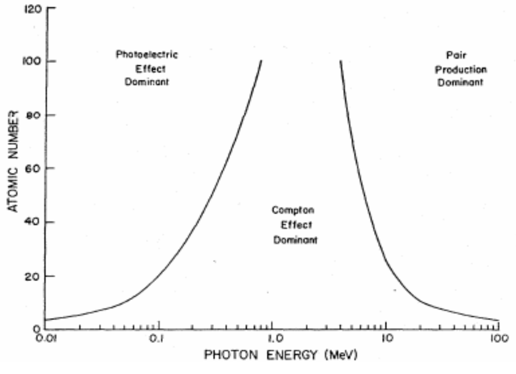


Fig 1: Effects of photon energy and atomic mass number of absorbing medium on dominant type of photon attenuation processes

The detection of photons is an indirect process, involving an interaction between the photon and the detector material which results in all or part of the energy being transferred to one or more electrons. It is only through the energy loss from these electrons that the γ -ray is converted into an electrical signal. For the signal to be a good representation of the energy of the incident photon it is desirable that the photon it is desirable that the photon energy is completely converted into kinetic energy of electrons in the material and that no energy escapes from the volume of the detector in the form of low energy or back scattered photons or secondary electrons. At the γ- ray energies of interest, three basic interaction processes are dominant in converting the incident photon energy into electrons in a detector:

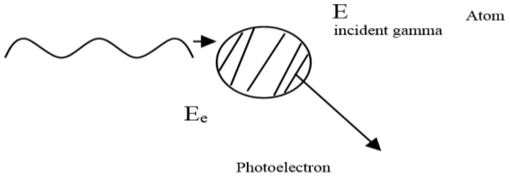
i) Photoelectric effect

This process results in the total absorption of the photon and the release of an from an atom of the detector material. The photoelectron energy is equal to the incident photon energy minus the binding energy of the electron in the atom.

$$Ee = E_{\lambda} - E_b$$

The X-rays subsequently emitted by vacancy filling in the shells of the atom are generally absorbed in a very short range within the detector, so the total signal corresponding to the total conversion or the original photon energy into kinetic energy of the electrons: The presence of a large mass is required to conserver momentum in the photoelectric process i.e. the interaction must be with a bound electron. The probability of an interaction is a strong function of the atomic no. in the absorbing material. The cross- section of the interaction, over the range of energies of interest and usual no. Z of detector material can be approximated:

$$\sigma_{pe} = k_{pe} Z^{4.5}/E^3$$



Where k_{pe} is a proportionality constant, σ_{pe} is the probability of a photon of energy E interaction with an a material of atomic no. Z . materials with higher atomic numbers have much larger cross- section therefore stop a much higher proportion of photons. Photoelectric absorption is the dominant interaction between γ rays and semiconductors below 100 keV. To detect the full energy peak, the final interaction in a full energy event must be of this type, since it is the only mechanism that does produce secondary photons. For this type of interaction, the full energy of the γ ray is transferred to the semiconductor material, effectively around the position where the interaction takes place.

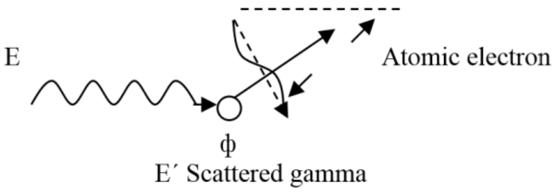
ii) Compton Effect

This is the classical :billiard ball" collision process whereby the photon strikes an electron resulting in the electron acquiring some of the photon's original energy and at the same time, producing a lower energy photon. The energy of the scattered photon is giving by

$$E = E^o/1+E^o\,(1 - \cos\theta)\,/\,m_0\,c^2$$

Where E^0 is the initial photon energy, m_0 is the rest mass of an electron and c is the velocity of light. For small scattering angles θ, very little energy is transferred. The maximum energy E max given to the electron in a head- on collision is:

$$E_{max} = E^0\,/1 + m_0\,c^2\,/2E^0$$



In a realistic experimental spectrum, the Compton Effect produces a distribution of γ –rays up to the energy given by Equation is known as the Compton edge. At higher incident photon energies, the photoelectric process become its probability is given by where k_{cs} is proportionality constant.

$$\sigma_{cs} = k_{cs}\,Z/E.$$

This is fortunate because the Compton-scattered photons stand a good chance of producing photoelectrons; in this case the summed energies of the Compton produced electron and the photoelectron is equal to E, and the double event appears as one count in the full amplitude peak. Over much of the γ-ray energy range of interest i.e. between approximately 200 keV and 2 MeV this double or multiple process contributes most of the counts in the full-energy peak. As a result the greater the γ-ray energy increases, the fewer full energy photoelectric event will occur. For this interaction mechanism, only part of the initial photon energy is transferred to the detector at the position of interaction. The probability for Compton scattering at an angel θ is predicated by the Klein-Nishina formula for the differential cross section per electron.

$$De\sigma/d = ½r2\ \{1/1 + \alpha(1\text{-}\cos\theta)^2\ [1+\cos^2\theta + \alpha^2\ (1\text{-}\cos\theta)^2/1 + \alpha^2(1\text{-}\cos\theta)]\}$$

In this expression α is the photon energy in unit of the electron rest energy and r_0 is a parameter called the classical electron radius.

$$r_0 = e^2\,/4\pi e_0\ m_0 c2 = 2.818\ f_m$$

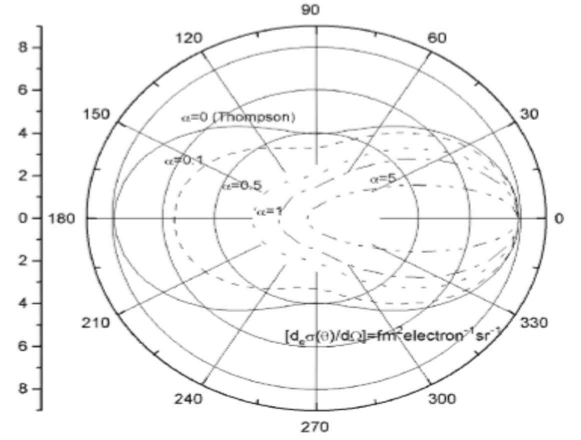


Fig: Differential cross-section dσ(θ)/dΩ for the production of secondary pho-tons from Compton scattering. Curves are shown for six different values of primary photon energy (α = 1,Eγ = 511 keV).

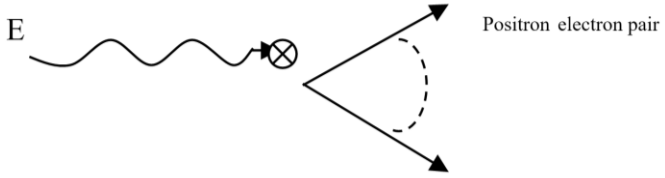
This is simply a convenient parameter and has nothing to do with the "size" of the electron. Inspection of the plot in fig. for the Klein-Nishina formula shows that the higher the γ-ray energy, the more improbable large scattering angles are.

iii) Pair production

This process can only take place when the incident photon energy exceeds the 1.022MeV required to create an electron-position pair. The excess energy greater than 1.022MeV is transformed into the shard kinetic energy of the electron and positron, which subsequently then produce ionization along their tracks. When the positron comes to rest, it annihilates with an electron in the detector material to produce two 511KeV photons which are emitted back-to-back in order to conserve momentum. The spectrum produced by this process always contains features whose relative intensities depend on the particular geometry of the detector. A full energy peak is produced when both 511KeV annihilation photons are absorbed in the detector, a peak in the spectrum at 511KeV less than the full energy corresponds to the escape of one 511KeV photon single peak while a third peak of 1.022MeV below the full energy peak, corresponds to the escape of both 511KeV photons the double escape peak. The cross section for pair production σpp is given by

$$\sigma_{pp} = k_{pp\,Z}{}^2\ \text{In}\ (E)\text{-}\ k_{pp}\ Z^2\text{In}\ (1.022\text{MeV}) = k_{pp}Z^2\ \text{In}\ (E)\text{-}\ \sigma_{pp}\ \text{th}$$

where σ_{pp} is a proportionality constant and the second term explicitly indicates the 1.022MeV threshold.



2. Research Study

For the typical γ-ray energies which are measured in nuclear physics studies, the dominant interaction process is Compton scattering. A γ-ray can interact by a Compton effect and the secondary γ-ray may escape the detector, contributing to the Compton background and decreasing the Peak-to-Total ratio P/T. This ratio can be improved if the detector is surrounded by a shield detector to veto the events.

For germanium detectors a scintillator made from Bismuth German ate Oxide is usually chosen due to its high average atomic number Z average = 27.6 and high density ρ = 7.12g/cm^{3}the probability of detecting γ-rays increases with the atomic number and density. If both detectors detect a γ-ray within a fixed time interval, the event is discarded from the spectrum.

From the cross-section for an interaction, the corresponding linear attenuation coefficient is defined as

$$\mu t = \sigma t\ N_{atom} = \sigma i \rho\ N\ A/M$$

where N atom, M, ρ NA are atomic densities, the molar mass, the density and the Avogadro Number. The linear attenuation coefficient gives the probability that a photon from a beam impinging on the detector interacts with the detector per unit path length.

For γ-rays, using Equations obtain,

$$\mu\ (E) = N_{atom}\ (k_{pe}.\ Z^{4.5}/E^3 + K_{cs}\ Z/E + K_p p\ Z2\ \ln\ (E) - \sigma_{ppth}$$

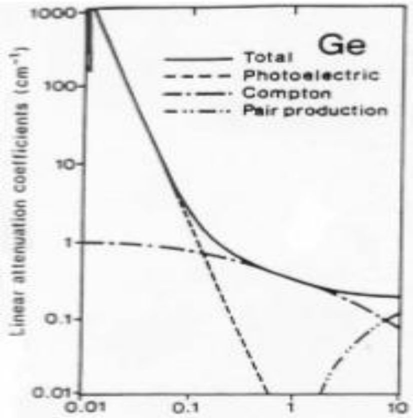


Fig: Gamma-ray linear attenuation coefficients for Ge as a function of γ-ray energy

Figure shows the different attenuation coefficients for the three types of interaction in Ge and the sum over the range of energies of interest. It demonstrates that Compton scattering dominates the deposition of energy between 150keV and 8MeV. In this range of energies, further interactions will be required to fully absorb the total photon energy in a detector.

If N_0 photons impinge on the detector material, the number of photons, N, after a length x which have not undergone an interaction is given by

$$N = N_0\ (1 - e^{-\mu x})$$

This attenuation is clearly related to the overall detection efficiency. The average distance traveled by a γ-ray in the detector before an interaction happens, is given by the mean free path λ, where,

$$\lambda = 1\ /\ \mu$$

And λ varies between a few tens of μm to a few cm in Ge depending on the γ-ray energy, and refers to the average after which the intensity of an incident photon is reduced by a rector of e^{-1}= 0.368. The dependence on the density ρ can be removed by using the mass attenuation coefficient μ/ρ.

For all interaction types, a high energy electron and in the case of pair production also a positron is released and it is only through its interaction with the material that the photon is detected. In a semiconductor the active volume for detecting charged particles is the depletion region of a reversed biased diode.

In this region, the electron is consumed by creating electron-hole pairs, but at higher kinetic energies, Bremsstrahlung increasingly contributes to the total energy transfer. For an electron with 1 Me V kinetic energy, Bremsstrahlung represents about 5% of the energy loss in Ge.

The energy transferred by the fast electron to the semiconductor per unit displacement is the sum of the specific energy loss of a charged particle in a material, given by the Bethe-Bloch formula where α is the fine structure constant, e, m0, are the electron charge and rest mass, c is the velocity of light in vacuum, of light in vacuum, E and v are the energy and velocity of the fast electron respectively, β = v/c, Z and N atom are the atomic number and atomic density in atoms/cm^3 of the detector material respectively and I is the average ionization potential of the material.

The total energy loss is simply the sum of these two terms:

$$(dE\ /\ dx)^{electron} = (dE\ /\ dx)^{electron}{}_{collision} + (dE\ /\ dx)^{electron}{}_{radiation}$$

Combining both equations, the average distance covered by an electron before completely depositing its kinetic energy in the detector can be calculated. It illustrates that in Ge the energy is transferred to the detector within a few mm of the electron being produced for all energies of interest.

Once the energy of the positron becomes comparable to the thermal energy of the electrons in the semiconductor crystal, it annihilates and at least two photons must be produced in order to conserve momentum. For the full energy of the positron to be deposited in the detector, all secondary photons must be absorbed. As the positron and the fast electron lose nearly the same energy and have the same properties, their ranges are comparable.

3. References

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