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REVIEW ARTICLE

**INTERACTION OF HEAVY CHARGE PARTICLE
WITH MATTER**

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Interaction of Heavy Charge Particle with Matter

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INTRODUCTION

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:

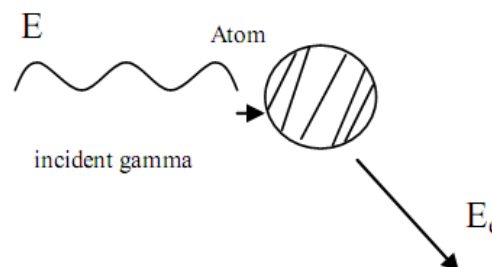
i) Photoelectric effect:

This process results in the total absorption of the photon and the release of an electron 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.

$$E_e = E_\gamma - E_b$$

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 conserve 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 atom 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.

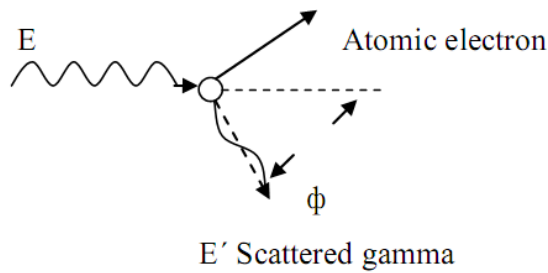
ii) Compton effect.

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 given by

$$E = E^0 / (1 + E^0 (1 - \cos \theta) / m_0 c^2)$$

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 angle θ is predicated by the Klein-Nishina formula for the differential cross section per electron.

$$d\sigma/d\Omega = \frac{1}{2}r_0^2 \left\{ \frac{1}{1 + \alpha(1-\cos\theta)^2} \left[1 + \cos^2\theta + \alpha^2 (1-\cos\theta)^2 / 1 + \alpha^2(1-\cos\theta) \right] \right\}$$

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.

$r_0 = e^2 / 4\pi\epsilon_0 m_0 c^2 = 2.818 \text{ fm}$ 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.

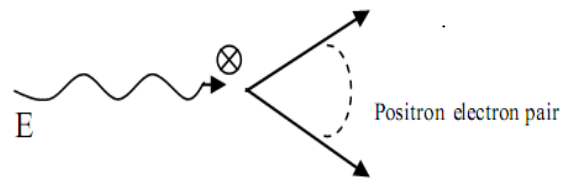
iii) pair production.

This process can only take place when the incident photon energy exceeds the 1.022MeV required to create an electron-positron pair. The excess energy greater than 1.022MeV is transformed into the shared 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 σ_{pp} is given by

$$\sigma_{pp} = k_{pp} Z^2 \ln(E) - k_{pp} Z^2 \ln(1.022\text{MeV}) = k_{pp} Z^2 \ln(E) - \sigma_{ppth}$$

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



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 Germanate Oxide is usually chosen due to its high average atomic number Z average = 27.6 and high density $\rho = 7.12\text{g/cm}^3$ 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

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

Where N_{atom} , M , ρ N_A 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,

$$\mu(E) = N_{\text{atom}} (k_{pe} \cdot Z^{4.5}/E^3 + k_{cs} Z/E + k_{pp} Z^2 \ln(E) - \sigma_{ppth})$$

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 factor 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 MeV 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 , m_0 , are the electron charge and rest mass, c is the velocity of light in vacuum, E and v are the energy and velocity of the fast electron respectively, $\beta = v/c$, 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:

$$\left(\frac{dE}{dx}\right)_{\text{electron}}^{\text{radiation}} = \left(\frac{dE}{dx}\right)_{\text{electron}}^{\text{collision}} + \left(\frac{dE}{dx}\right)_{\text{electron}}^{\text{radiation}}$$

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.

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