NUCLEAR SCIENCE

RADIATION

EXPERIMENT: Absorption of Beta Particles in Aluminum

OBJECTIVES

- To study the absorption properties of beta particles.
- To observe the nature of the interaction of beta particles with aluminum metal
- To determine the half-value thickness and the mass absorption coefficient for beta particles with two different maximum energies in aluminum metal.

THEORY

Experimental evidence shows the beta particle to be identical with the electron. It has a rest mass of 9.1 x 10^{-28} grams and a charge Q of 1.6 x 10^{-19} coulombs. Thus, we conclude that the principal distinction between an electron and a beta particle is the source or origin. An electron emitted from a nucleus is called a beta particle.

The velocity of a beta particle is dependent on its energy. Velocities range from zero continuously up to about 2.9 x 10^{10} cm/sec, or nearly the velocity of light. Classically, the energy of the beta particle is given by the expression

$$E_\beta = 1/2mv^2$$

This equation is quite useful for small values of v, but at higher velocities the following relativistic correction, as proposed by Einstein, is required

$$E = \frac{mc^2}{\sqrt{\left(1 - \frac{v^2}{c^2}\right)}}$$

Here, m is the mass of the particle, which is an invariant, v is the velocity of the particle, and c the velocity of light.

<u>Beta spectra</u> - It has been determined experimentally that beta particles have a continuous energy spectrum and that a part of the decay energy is carried away by neutrinos. The shapes of these spectra differ among nuclides, the shape being a function of the type of nuclear transition. (Beta transitions are referred to as "allowed", "forbidden", etc. to indicate nuclear conditions related to stability.) Ra-E (^{210}Bi) which is frequently used as a standard, decays by a "forbidden" transition and hence has a spectrum that peaks in the low energy region (see Figure 1). The average energy of the beta particles lies between one-fourth and one-third of E_m. In some instances sharp peaks are found in

the beta spectra. These are caused by beta emitters that produce conversion electrons. ^{137}Cs is a typical example.

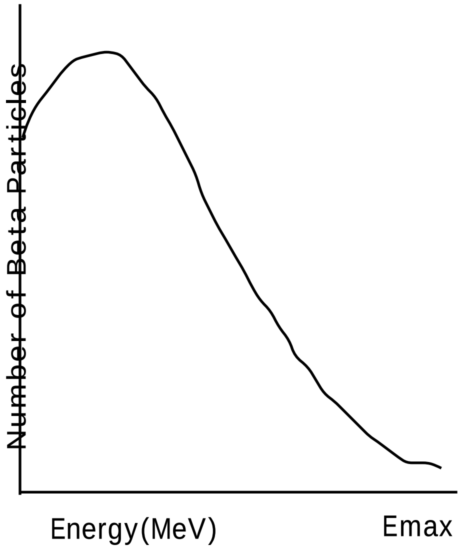
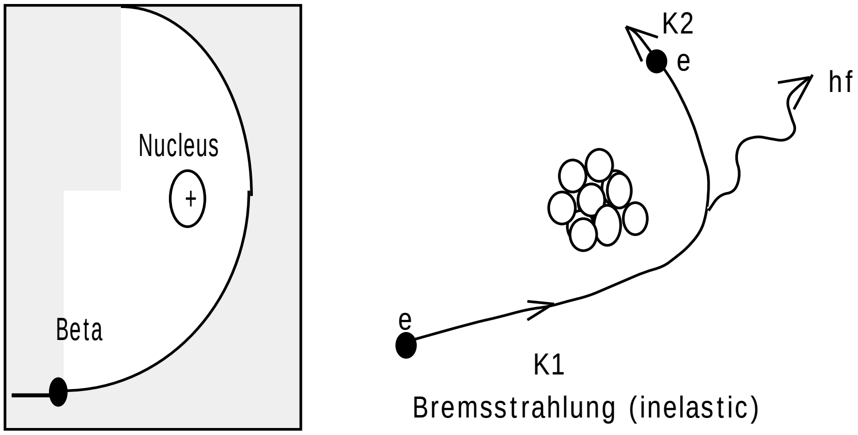


Figure - BETA SPECTRUM FOR Ra-E (^{210} BI)

<u>Beta-particle interactions with nuclei</u> - A collision of a beta particle with an atomic nucleus involves a coulomb interaction in which the electron is sharply deflected in its path. If this interaction is elastic, the process is called Rutherford scattering, and the energy of the emergent beta particle is essentially equal to that prior to the collision. This can be deduced from the fact that the total kinetic energy for the colliding systems has not changed (the collision was elastic) and since the atom is at least several thousand times heavier than the electron, the recoil energy of the atom will be negligible. Rutherford scattering is primarily responsible for back-scattering of beta particles.



Bremsstrahlung (inelastic)

Elastic Scattering

Figure - SCATTERING OF A BETA PARTICLE

When electrons are slowed down, decelerated, in the coulomb field of an atomic nucleus electromagnetic radiation called bremsstrahlung is produced. This radiation is characteristic of the target and of the beta particle energy, but is a continuous band and usually amounts to about 1% of the total radiation. The percentage of bremsstrahlung production increases with the atomic number of the absorbing material. Hence, for shielding for protection against beta radiation, it is customary to use a material of low atomic number, such as plastics. Bremsstrahlung are produced by the inelastic interaction of a beta particle with the nucleus. The total kinetic energy of the colliding systems is less by an amount equal to the energy radiated as Bremsstrahlung.

Beta-ray interactions with orbital electrons - Particles possessing like charges repel each other. The coulomb repulsion between a beta particle and one of the orbital electrons in the substance being traversed by a beta ray may be sufficient to expel the electron completely from its atom. The atom then becomes a positively charged ion. After this ionization process, the final energy of the electron E_f is less than the initial energy E_i by an amount equal to the sum of the binding energy _ of the ejected electron and its kinetic energy. That is,

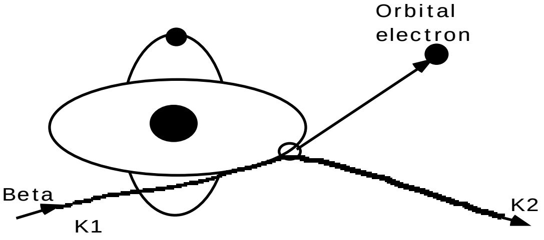


Figure - IONIZATION
(inelastic collision)

$$E_f = E_i - (\varphi + 1/2mv^2)$$

In collisions involving the expulsion of K, L or M electrons from an atom, characteristic x-rays are produced as electrons fall back into the ground state.

$$E_{photon} = h\nu = E_{excited} - E_{ground}$$

<u>Absorption of beta particles in matter</u> - The absorption of beta particles by matter, from a macroscopic point of view, is a function of the distance traveled by the particles through the absorbing material and the density of the material. The product of these two variables, the density times distance has the units grams cm^{-2} or often, for convenience, **mg cm^{-2}**. This value is used to express the absorber thickness.

Let a beam of beta particles of intensity Io impinge upon a single absorber as shown in the following figure. Some of these beta particles will be absorbed so the reduced intensity of the emerging beam is I. It has been observed that the absorption of beta particles is approximately an exponential function of the density "_" of the absorber and the distance "X" through the absorber, and "μ " the absorbing property of this particular material. Hence, the absorption of beta particles is approximately analogous to the absorption of light, and the mathematical relationship for beta absorption takes the same form as the familiar Beer-Lambert Law.

$$\ln\left(\frac{I_0}{I}\right) = \frac{\mu}{\rho}\, x\rho \qquad (1)$$

Since "X" is measured in cm and the density in mg/cm3, the units of the product "X_" are mg/cm^2. Consequently "μ / ρ", the mass absorption coefficient, has the units cm^2/mg.

Because the observed activity R is proportional to intensity I, the equation can be written.

$$\ln\left(\frac{R_0}{R}\right) = \left(\frac{\mu}{\rho}\right) x\rho \qquad (2)$$

where R_o is the observed activity without absorber and R the observed activity with absorber. This can be expanded into a more useful form to be used with the experimental measurements:

$$\ln(R) = \ln(R_0) - \frac{\mu}{\rho}\, x\rho \qquad (3)$$

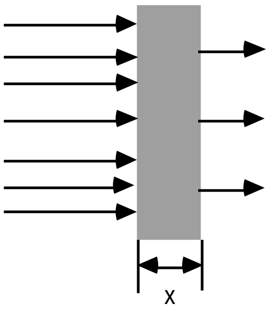


Figure - ABSORPTION OF BETA PARTICLES.

The density of the absorber is ®.
The distance through the absorber
is X. The absorber "thickness" x = ®X.

If the logarithm of the activity is plotted against the thickness of absorber placed between the sample and the detector, a straight line is expected, however, a curve will be obtained. A straight line is not obtained but rather one that is slightly curved. This is contrary to the prediction made by the theory that is expressed by equation (3). This is an indication that more than one absorption process is taking place. In the upper left part, however, the curve may be assumed to be linear and the slope can be determined.

It is important to note that the observed activity is a function of the position of the absorber. As the absorber is moved to a position closer to the source, the activity will be seen to increase. This increase in activity is caused by scattering of the beta particles from the absorber. The absorber should therefore be located close to the window of the detector as illustrated in the following figure.

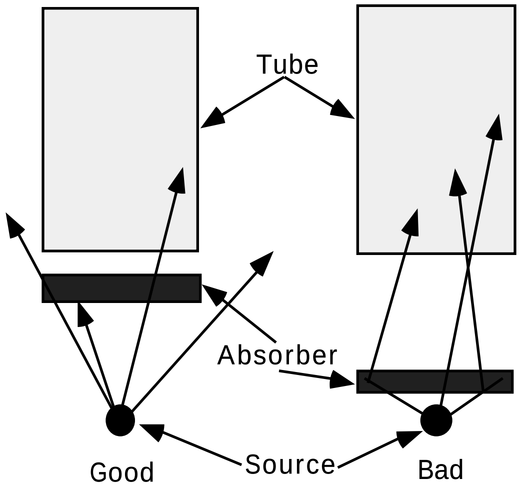


Figure - INFLUENCE OF ABSORBER
LOCATION IN MEASUREMENTS OF Beta RAY ABSORPTION.
(a) if good geometry is used beta-particle scattering is minimized.
(b) if the absorber is placed directly on or near the source, beta particles are scattered into the tube.

Apparatus:

Geiger tube and scalar; set of aluminum absorbers (17 discs from 1.7 to 1670 mg/cm^2), two beta sources with different energies: Thallium-204(3.81y), Beta (0.765 MeV); Yttrium-90 (64hr), Beta (2.3 MeV); Carbon-14, Beta (0.156 MeV).

Procedure:

The absorption of radiation in a given medium can be used in the identification of a radioactive isotope. The absorption coefficient μ / ρ using the aluminum absorbers of graduated thickness, mg/cm^2, is determined to characterize the beta radiation emitted by a radioactive isotope. In determining the type and energy of the radiation from a source, an absorption curve of detected radiation verses $x\ \rho$ for the absorber is determined. The unknown type can then be determined by comparison with the known absorption characteristics of different types and energies of radiation.

Complete the following procedure for three radioactive isotopes with Beta particle radiation of three different energies, one small, medium and one much larger.

- 1. The absorber should be kept as close to the source as possible.

- 2. The counting rate of the source with the empty absorber (#17) should be determined and the source and absorber then used as far from the detector as possible consistent with a substantial detector rate. This reduces the effects of resolution loss in the counting equipment, and in conjunction with 1 (above), reduces the effects of scattered radiation. This is of particular importance in the case of beta radiation.

- 3. Background radiation should be accurately determined and its value subtracted from all readings before plotting them on the absorption curve. For sources that emit no gamma radiation, the background should be run with the source in place and its radiation completely absorbed in aluminum using absorber #18. In this manner, the contribution to the background from bremsstrahlung will be included.

- 4. Information about the approximate type of radiation emitted is helpful in determining the range of absorbers to be used. Where this information is not known in advance, an initial run using widely spaced values of absorbers will guide the subsequent determinations. A typical run might include absorbers number 17 (blank), 7, 12, 18 and 24.

- 5. As is illustrated in the theory section, it is usually desirable to plot the absorption curves with the absorber density ($x\ \rho$) on x-axis and the natural log of the detected count rate on the y-axis.

- 6. The total absorber thickness is the thickness of the aluminum in mg/cm^2 plus the thickness of the Geiger-Muller window (given by manufacturer), plus the air thickness. There is a problem however; the absorption coefficients for these materials are all different. Therefore it will be necessary to write out the equations for absorption through three different materials before the betas are detected by the Geiger-Muller tube. Using this equation it is possible to determine what the slope and intercepts of the absorption curve represents. The absorption coefficient for air can be found in the literature, but the absorption coefficient for the tube window is not known. It may be possible to calculate this value from the absorption counting data. (Consider the system when there are no aluminum absorbers in the path of the beta radiation, just the air and the mica window.)

- 7. If more than one type of activity is present, and if the range of half thickness of each type is widely separated from the others, then reasonably good results can be obtained by running the curves with the thicker absorbers first, and then subtracting out the intensity of the more penetrating radiation when making the measurements of the less penetrating ones.

- 8. For beta radiation the curve will be approximately exponential or linear on a semi-log plot. The first section of it and will drop off more rapidly as the range of the betas of maximum energy is approached. From this curve determine the absorption coefficient μ / ρ and compare to the known values.

- 9. The maximum energy of the beta particles can only be approximated by comparing the maximum range from your curve to a standard Beta Range-Energy Curve that is supplied with the absorber set. The maximum range of the beta particles is very difficult to determine with great accuracy. The greatest uncertainty is incurred at the low measured activities. From your curve approximate the maximum range and determine the maximum energy of the beta spectrum. Compare to the known value for this source.

- 10. The absorption coefficient will be a function of the energy of the Beta particle. Determine this functional relationship using the experimentally determine absorption coefficients for the three different Beta particle energies.

NUCLEAR SCIENCE

Radiation Physics

Experiment: Scintillation Tube

To determine the operating voltage of a scintillation tube.

Introduction

The Geiger tube is the best known device for making radioactive measurements. However, the Geiger tube has serious problems in measuring gamma radiation. Most gamma rays will pass through a Geiger tube undetected.

Scintillation tubes, on the other hand, are very sensitive to gamma rays. The tube works by having the gamma rays interact with a crystal to give off light. This light is detected by a photocell, known as a photomultiplier. The photomultiplier has a system of dynodes within the tube that can amplify the signal from a photocathode as much as a million times.

Materials

Geiger-system, Scintillation tube, lead bricks, Co-60 (1 microcurie), Sr-90 (.1 microcurie), Po-210 (.1 microcurie).

Procedure

- 1. Place the scintillation tube in the lead shield and have the Co-60 source about five (5) centimeters from the window.

- 2. Connect the high voltage wire from the back of the Geiger system to the high voltage connection on the tube's base. Take another wire and run it from dynode connections on the tube's base to pre-amp input. Adjust the pre-amp for a gain of sixteen (16). Now run a wire from the amp output to the input of the counter.

- 3. Turn on the Geiger system, adjusting the high voltage to five hundred (500) volts. Set the timer to make ten second counts.

- 4. Make and record the counts for five hundred (500) to fourteen hundred (1400) volts at fifty (50) volt increments.

- 5. After an operating voltage has been determined, take and record five one minute background counts. Then take and record five one minute counts for the Sr-90 and Po-210 sources.

Analysis

- 1. Determine a good operating voltage for the scintillation tube by plotting counts versus voltage.

- 2. The Co-60 source is a gamma emitter, Sr-90 is a beta emitter and Po-210 is an alpha emitter. Knowing this information, subjectively rate the efficiency of the scintillation tube at detecting each of these radiations.

NUCLEAR SCIENCE

RADIATION PHYSICS

Experiment: Absorption and Energy of Gamma Photons

Objectives:

- To study the nature and source of gamma rays.
- To observe the modes of interaction of gamma rays with matter.
- To measure the linear and mass absorption coefficients.
- To estimate the energy of gamma emission from a given source.

Theory

Gamma radiation, unlike alpha and beta nuclear radiation, is an electromagnetic wave. Gamma radiation is thus radiated as photons or quanta of energy which travel with the velocity of light, c = 3.0 x 10^{10} cm/sec. Gamma radiation differs from x-rays, visible light, radio waves, etc., only in wavelength λ or frequency υ. Wavelength and frequency are related to the velocity of light by the equation,

$$\lambda = \frac{c}{\upsilon} .$$

The energy of a photon can be calculated by use of the relationship

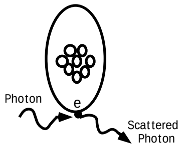
$$E = h\upsilon$$

where E is the energy in ergs or Joules, h is Planck's constant (6.624 x 10^{-27} erg sec or x 10^{-34} Joules sec) and υ is the frequency in vibrations per second.

A significant difference between x-rays and gamma rays is their source. The source of x-rays is extra-nuclear, that of gamma rays intra-nuclear. The process by which x-rays are produced is identical to that producing bremsstrahlung. In an x-ray tube, high velocity electrons are generated and allowed to impinge on a target. The electrons undergo inelastic collisions with target nuclei that result in the deceleration of the electrons and the emission of electromagnetic radiation. Inelastic collisions with orbital electrons cause ionization and the production of characteristic x-rays.

Gamma rays are produced by nuclear energy transitions. For example, when cobalt-60 decays by beta emission, nickel-60 is produced. The process not only involves the emission of a beta particle, but of two gamma quanta as well. Electromagnetic radiation is also emitted during decay by electron capture.

When a photon interacts with matter, the collision may occur with a nucleus, an electron or with the field about the nucleus. This collision may be elastic, inelastic or may result in the complete absorption of the photon. Interactions of some importance are Rayleigh scattering, photodisintegration, nuclear resonance scattering, Bragg scattering and Thomson scattering while the photoelectric effect, the Compton effect and pair production are of major importance in the utilization of radioisotopes.



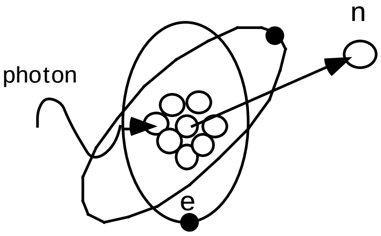


Figure 1 - Thomson Scattering **Figure 2**-Photo-disintegration

Rayleigh scattering - If the interaction between a photon and an orbital electron is insufficient to produce ionization or excitation of the atom, the collision is elastic and the energy of the photon is the same after the collision as it was before. Rayleigh scattering rarely results in scattering of the photon through more than a few degrees.

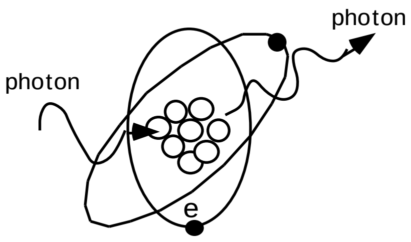
Thomson scattering - It was first thought that x-rays should be reflected from a mirror the same as visible electromagnetic radiation. Soon after their discovery it was observed that they are scattered rather than reflected. J.J. Thomson explained this scattering as an interaction of x-rays with orbital electrons. The electrons are presumed to absorb the electromagnetic radiation, oscillate in an excited state and re-radiate the x-radiation in random directions.

Photodisintegration - Here the interaction involves a collision of a high-energy photon with a nucleus. The photon is completely absorbed in the process, and a neutron, proton or alpha particle is ejected from the excited nucleus. (See Fig. 2). The following are typical examples of photodisintegration:

$$^{2}_{1}\mathrm{D} + \gamma \rightarrow {}^{1}_{1}\mathrm{H} + {}^{1}_{0}\mathrm{n}$$

$$^{9}_{4}\mathrm{Be} + \gamma \rightarrow {}^{8}_{4}\mathrm{Be} + {}^{1}_{0}\mathrm{n}$$

Nuclear resonance scattering - If the vibrational frequency of a nucleus is equal to that of an incident photon, absorption of the photon may occur. The photon is then re-emitted from the excited nucleus. In 1961, R.L. Mossbauer received the Nobel Prize for his resonance experiments with the iron isotope Fe^{57} excited by radiation from the decay of Co^{57}. Detection of this Mossbauer effect is accomplished by means of a Doppler effect by moving the Fe^{57} target with respect to the Co^{57} source to compensate for the energy of recoil of the Fe^{57} nucleus. Mossbauer's work is of considerable importance to physics. (See Fig. 3).



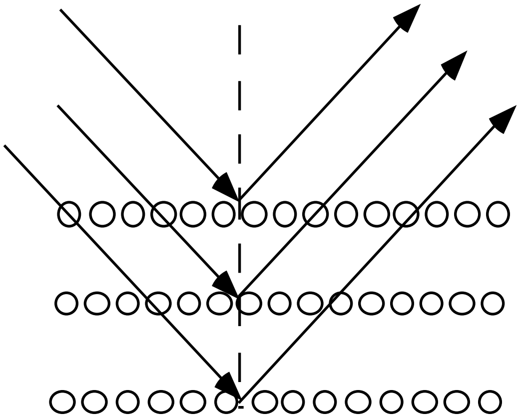


Figure 3 - Nuclear Resonance **Figure 4** - Bragg Scattering

Bragg scattering occurs with gamma rays in the same manner that the Bragg scattering of x-rays (x-ray diffraction) takes place at a crystal face. It is an elastic coherent type of scattering. It is said to be coherent because there are definite phase relationships between the incident and scattered waves.

$$n\lambda = 2d \sin(\Theta)$$

If the angle theta at which the radiation strikes the face of the crystal is related to the wavelength lambda of the incident radiation and the distance "d" between planes of atoms within the crystal by the Bragg equation such that "n" is a small, whole number, reinforcement of the intensity of radiation will occur. This phenomenon, incidentally, affords us one of the most accurate procedures by which the wavelength may be determined. (See Fig. 4).

The Photoelectric effect occurs principally when the photon energy is low. The inelastic collision of the photon with the orbital electron results in the complete ejection of the electron and the production of an ion pair. The kinetic energy of the ejected electron is given by the equation,

$$1/2mv^2 = h\upsilon - \Phi$$

where Φ is the work function or binding energy of the electron. This means that the total energy imparted to the electron by the photon is equal to that required to remove it an infinite distance from the nucleus Φ plus the kinetic energy of the electron $1/2mv^2$. In this process, a K-electron is usually involved. The photoelectric effect is most pronounced if the atomic number Z of the absorbing material is high. (See Fig. 5).

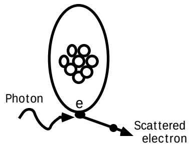


Figure 5 - Photoelectric effect

The Compton effect or Compton scattering is especially important for gamma rays of medium energy (0.5 to 1.0 MeV). It involves a collision between a photon and an electron in which a part of the energy of the photon is imparted to the electron. The photon emerges from the collision in a new direction and with reduced energy. Considering that both energy and momentum must be conserved in the collision, we can derive the following relationship:

$$\lambda' - \lambda = \frac{h}{mc}(1 - \cos(\Phi))$$

Thus, the change in wavelength of the photon is related to the cosine of the scattering angle Φ The term h/mc is called the Compton wavelength λ_0 and has the value 2.43 x 10^{-10} cm. (See Fig. 6).

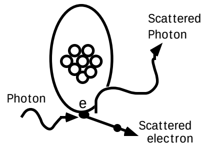
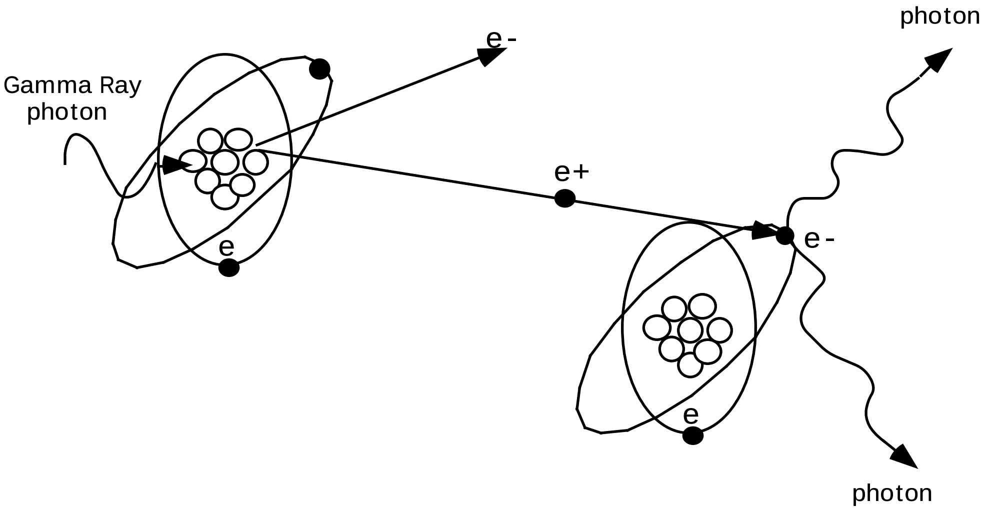


Figure 6 - Compton Scattering

Pair production is involved only with gamma rays having energies greater than 1.02 MeV. The energy of the gamma ray is converted into an electron and a positron in the region of a strong electromagnetic field such as that surrounding the nucleus. Photon energy in excess of 1.02 MeV appears as the kinetic energies of the electron and positron produced.

$$E = h\upsilon = 2mc^2 + T_{e^-} + T_{e^+}$$

where 2 mc^2 = 1.02 MeV and represents the energy required to form the pair of particles according to the Einstein equation, E = mc^2. Te- and Te+ are the kinetic energies of the electron and positron, respectively. (See Fig. 7).



PAIR PRODUCTION.

Figure 7

EXPERIMENT THEORY:

As gamma radiation passes through matter, it undergoes absorption by interacting with atoms of the absorbing material, principally by the photoelectric effect, the Compton effect, and by pair production. The result is a decrease in the intensity of the radiation with the distance traversed through the absorbing material. The decrease in the energy of an incident beam of gamma radiation is exponential in form, as expressed by Lambert's law:

$$I = Io\ e^{-\mu X}$$

or

$$\ln(I/Io) = -\mu X$$

Here Io is the intensity of the incident beam of photons, I is the intensity after traversing a distance X through the substance and μ is the linear absorption coefficient.

A useful concept regarding gamma absorption is the Half-Value-Layer (HVL) or the half-thickness $X_{1/2}$ which is defined as the distance of travel through an absorber required to decrease the intensity of a beam of gamma rays to one-half its initial value. Thus, after a ray has passed through a half-thickness of absorber, the intensity of the beam I is equal to 1/2Io. Rearranging the equations and substituting 1/2Io for its equal, I, one obtains

$$X_{1/2} = HVL = 0.693/\mu$$

Half-value-layers (values of half-thickness) for aluminum and lead can be found in the literature.

The linear absorption coefficient μ, the value of which depends upon the nature of the absorbing material, has the units cm^{-1}. The mass absorption coefficient μ' is defined as μ/ρ and has the units cm^2/g, where ρ is the density of absorbing material. If ln(I) is plotted versus absorber thickness in centimeters, the slope of the curve gives -μ, the linear absorption coefficient. If ln(I) is plotted versus absorber thickness in grams per square centimeter (g/cm^2), the slope is equal to $-\mu/\rho$, the mass absorption coefficient.

It has been shown that when the log of the intensity is plotted versus the absorber thickness, an essentially straight line is obtained, indicating a linear relationship and the constancy of the coefficient. That this should be so seems somewhat miraculous in view of the fact that μ is the sum of no less than three other coefficients showing dependency on the gamma ray energy; namely, the atomic number, the mass the density of the absorbing medium, as well as other factors. Thus,

$$\mu = \tau + \sigma + \kappa$$

where τ = photoelectric absorption coefficient,
σ = Compton scattering coefficient,
and κ = pair production coefficient

Contributions from Rayleigh scattering, Bragg scattering, photodisintegration and nuclear resonance scattering are negligible.

The photoelectric absorption coefficient is a function of the density ρ of the absorbing medium, the atomic number Z and the mass number A of the absorbing material, as well as of the wavelength λ and hence of the energy of the radiation. The coefficient is given by the expression,

$$\tau = 0.0089\rho \frac{Z^{4.1}}{A} \lambda n$$

where n = 3 for the elements N, C and O,
and n = 2.85 for other elements below Fe.

It is evident that photoelectric absorption is most pronounced for low energy gamma radiation (less than 0.5 MeV) and that it increases rapidly with an increase in the atomic number of the absorber. The mass photoelectric absorption coefficient τ' is related to the linear photoelectric coefficient by $\tau' = \frac{\tau}{\rho}$.

The Compton scattering coefficient consists of two components

$$\sigma = \sigma_a + \sigma_s$$

σ_a is the scattering coefficient dependent on the loss of energy to electrons in collisions. σ_s is the scattering coefficient dependent on the loss of energy due to the scattering of photons out of the beam.

If the energy of a quantum is greater than 2 X 0.51 MeV, an electron-positron pair can be formed. The pair formation coefficient K can be evaluated from the relationship,

$$K = a N Z^2 (E - 1.02)$$

where a is a constant, N the Avogadro number, Z the atomic number, and E the photon energy in MeV.

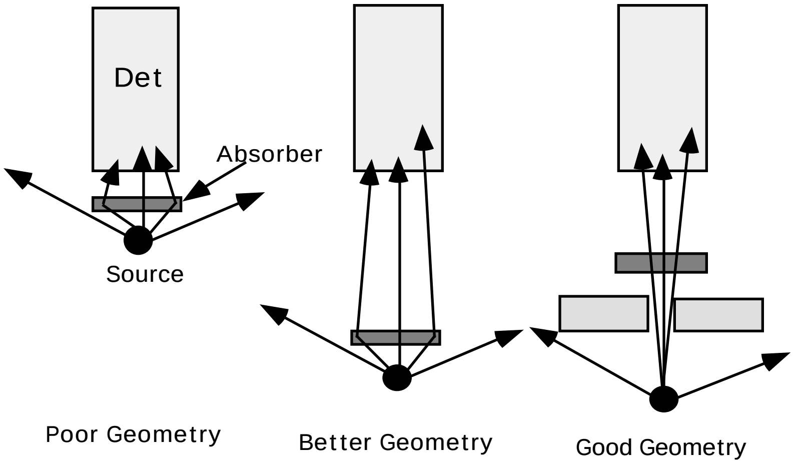
Geometry - the absorption coefficient μ, discussed in the preceding paragraphs, is more correctly referred to as the total absorption coefficient. This is the coefficient describing the decrease in beam intensity due to true absorption and to the scatter of radiation.

Total absorption coefficient = True absorption coefficient + scatter absorption coefficient. This same statement is expressed in symbols by

$$\mu = (\tau + \sigma_a + \kappa) + \sigma_s$$

Total = True+ scatter

If the total absorption coefficient is to be measured, it is necessary to establish " good geometry" so conditions required for narrow-beam attenuation are achieved. Conditions considered good are illustrated in Figure 8(c). Gamma rays from the source have been collimated so that only a narrow beam strikes the absorber. Compton scattered radiation produced in the absorber is then preventing from reaching the detector by additional shielding.



BROAD-BEAM AND NARROW-BEAM GEOMETRY
Figure 8

When the geometry is "poor", the attenuation is called "broad-beam". Such conditions are shown in Figure 8(a) where Compton scattered radiation from the absorber as well as from the shield strikes the detector. Measured activities will be higher under poor conditions than under good conditions since the attenuation is less.

Although good geometry is used to measure μ or μ', sometimes used for the identification of nuclides, it is important to consider scattering conditions prevailing when calculating the thickness of shielding required for safe handling or storage of gamma emitting isotopes. When in doubt, it is good practice to use $\mu' - \sigma' s$ for the calculation because shielding almost always creates poor geometry.

Buildup - Narrow-beam geometry will yield the exponential curves while broad-beam geometry will cause a definite increase in activity. This departure from the narrow-beam curve is measured by the buildup factor B which is defined simply as the ratio of the observed activity to the activity expected from total absorption (i.e., good geometry).

B = (Rate observed using absorber of thickness x)
divided by
(Rate calculated for total absorption using same absorber)

Buildup can be estimated by

$$B = 1 + \mu X \qquad \text{or} \qquad B = 1 + \mu' X$$

where μX and μ'X are equal to the absorber thickness in mean free paths.

Apparatus:

Geiger or scintillation counting assembly; gamma-ray sources (e.g. Co^{60}, Cs^{137}); calibrated lead absorbers or sheets of lead and micrometer caliper; aluminum absorbers; 3/8" plastic sheet.

Procedure:

In this experiment the total absorption coefficient is to be determined. Various arrangements of equipment can be used, the choice depending upon what is available.

Use of G-M counter - Directly above, and close to the source is placed a sheet of 3/8" plastic to absorb the beta particles, thereby decreasing the production of bremsstrahlung. Gamma rays from the source will pass quiet freely through the plastic. Lead absorbers of graduated thickness are then placed directly on top of the plastic. Finally, an aluminum absorber (400 mg/cm^2 to 600 mg/cm^2) is placed as close to the tube window as possible and allowed to remain there for all measurements. Its purpose is to filter out at least a part of the low energy scattered radiation. The source strength should be sufficient to give an activity of several thousand counts per minute with no lead absorber.

Use of scintillation detector - If a scintillation detector is available, it should be used in preference to the G-M tube. All other conditions, including the use of the aluminum absorber and sheet of plastic, should remain unaltered. The major advantage in the use of a scintillation detector is its high sensitivity to gamma radiation thus allowing the use of a much weaker radioactive source. Furthermore, the high voltage applied to the scintillation detector can be carefully increased until the counter just begins to record the primary radiation from the source. It will then be insensitive to low energy scattered radiation. A more accurate measure of μ is thereby possible.

Calibration of lead absorbers - Pre-calibrated lead absorbers may, of course, be used but these are unnecessary since a few pieces of sheet lead and a micrometer caliper will serve well. The thickness X (in cm) of each sheet of lead is measured with calipers and recorded. If the thickness x (in g/cm^2) is desired, it is calculated by use of the density since $x = X\rho$. The calibrated sheets of lead are used in combination to attain the desired thickness.

I. Measure the activity of the sample beginning with no lead absorber. Then proceed through the set of absorbers, singly or in combination, until the activity has decreased to 50% of the original value. Plot the resulting data on semi-log paper. Calculate the values of:

1. the half-value layer
2. the linear absorption coefficient
3. the mass absorption coefficient
4. the gamma energy

II. Repeat this procedure using aluminum absorbers. Calculate also the half-value-layer, the linear absorption coefficient and the mass absorption coefficient. Compare these values with those obtained with the use of lead absorbers and explain the results.

Use only the thicker aluminum absorbers and use them in combinations to obtain greater absorber thickness.