GAMMA DECAY

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GAMMA DECAY

Most α and β decays, and in fact most nuclear reactions as well, usually leave the final nucleus in an excited state. These excited states decay rapidly to the ground state through the emission of one or more γ rays, which are photons of electromagnetic radiation like X rays or visible light.

The nucleus makes the transition from the higher energy state, E_i, to the lower energy state, E_f, and gives out the excess energy

$$\Delta E = E_i - E_f$$

by means of one of the following three processes.

- Gamma-ray emission
- Internal conversion
- Internal pair-production

GAMMA DECAY

Gamma rays have energies typically in the range of 0.1 to 10 MeV, characteristic of the energy difference between nuclear states, and thus corresponding wavelengths between 10^4 and 100 fm.

These wavelengths are far shorter than those of the other types of electromagnetic radiations that we normally encounter; visible light, for example, has wavelengths 10^6 times longer than γ rays.

As the nucleus has discrete energy levels, the gamma spectra of nuclei consists of sharp lines. The energy of a gamma ray emitted is given by the relation

$$h\nu = \Delta E = E_i - E_f \qquad (1)$$

GAMMA DECAY

Unlike alpha and beta decay, the gamma decay does not cause a change in the atomic number or mass number of the nucleus. As compared to the half-lives of alpha and beta emitters, the gamma emitters have very short half-lives.

Gamma rays are electro-magnetic waves of very high penetrating power. They do not cause much ionization and are not deflected by the electric or magnetic fields. See Fig. 9.1. in Fundamentals of Nuclear Physics by Atam P. Arya in Fig. 9.1. for emission of gamma rays following alpha and beta decay.

ABSORPTION COEFFICIENT OF PHOTONS

The intensity of a beam of x-rays or γ-rays passing through a material follows the exponential law of absorption, because the change in intensity is directly proportional to the incident intensity and the thickness of the material.

Let us consider a beam of photons with intensity I falling perpendicular to a material of thickness Δx. Then the change in intensity, ΔI, is given by

$$\Delta I = -\mu I \Delta x \qquad (2)$$

where μ is the proportionality constant and is known as the absorption coefficient. For a homogeneous radiation, μ is constant and from Eq. 2 we get

$$I = I_0 e^{-\mu x} \qquad (3)$$

ABSORPTION COEFFICIENT OF PHOTONS

Where I is the intensity of the beam after the beam of initial intensity, I_0, has crossed a thickness x of the material.

Gamma rays do not have a definite range as do alpha and beta particles but are characterized by the attenuation absorption-coefficient, μ. Also, we may write

$$I = h\nu\phi \tag{4}$$

where $h\nu$ is the energy of each photon, and ϕ is the number of photons crossing a unit area in a unit time and is called the flux. Combining Eq. 3 and 4, we get

$$\phi = \phi_0 e^{-\mu x} \tag{5}$$

Where ϕ_0 is the initial flux.

ABSORPTION COEFFICIENT OF PHOTONS

Note that *I* denotes the energy flux (or intensity), and ϕ is the number flux. μ is sometimes called the *linear absorption coefficient*.

Besides the linear absorption coefficient, μ , the other coefficient that are commonly used are mass absorption coefficient, μ_m, atomic absorption coefficient, ${}_a\mu$ and electronic absorption coefficient ${}_e\mu$. These four coefficients are related to each other in the following way:

$${}_a\mu = Z\,{}_e\mu$$

$$\mu = \frac{\rho N_A}{A}\,{}_a\mu = \frac{\rho N_A Z}{A}\,{}_e\mu$$

$$\mu_m = \frac{\mu}{\rho} = \frac{N_A\,{}_a\mu}{A} = \frac{N_A Z}{A}\,{}_e\mu$$

where Z is the atomic number, A is the atomic weight, ρ is the density in g/cm^3, and N_A is Avogadro's number. Because μx is a dimensionless quantity, if x is expressed in cm, μ will be in cm^{-1}.

ABSORPTION COEFFICIENT OF PHOTONS

The half-thickness, $x_{1/2}$, is the characteristic of the absorber as the half-life is of the decaying nucleus. $x_{1/2}$ is defined as the thickness that reduces the incident beam intensity to one-half of its initial intensity,

$$I / I_0 = 1/2 = e^{-\mu x_{1/2}} \quad or \quad x_{1/2} = 0.693/\mu \qquad (6)$$

If the incident beam consists of photons of different energies, Eq. 5 is replaced by the following equation.

$$\phi = \phi_{01} e^{-\mu_1 x} + \phi_{02} e^{-\mu_2 x} + \phi_{03} e^{-\mu_3 x} + \ldots\ldots \qquad (7)$$

Where ϕ_{01} , ϕ_{02} , ϕ_{03} , …and μ_1 , μ_2 , μ_3 , … are the initial fluxes and absorption coefficients, respectively, of photons with energies $h\nu_1$, $h\nu_2$, $h\nu_3$,……

INTERACTION OF GAMMA RADIATION WITH MATTER

The gamma rays emitted in nuclear decay usually have energies ranging from a fraction of a MeV to a few MeV. In this range, the three main processes by which photons lose their energies by interaction with matter are:

- Photoelectric Effect (P. E.)
- Compton Effect (C. E.) or Compton Scattering
- Pair Production (P. P.)

These three processes are dominant in different ranges of the photon energy: The photoelectric effect from ~ 0.01 MeV to ~ 0.5 MeV, the Compton scattering from ~ 0.1 MeV to ~ 10 MeV, and pair production starts at 1.02 MeV and increases with increasing gamma energy.

INTERACTION OF GAMMA RADIATION WITH MATTER

All three processes are independent each other and by analogy with Eq. 2, we may write

$$(\Delta I)_{P.E.} = -\mu_\tau I \Delta x \qquad (8a)$$

$$(\Delta I)_{C.E.} = -\mu_\sigma I \Delta x \qquad (8b)$$

$$(\Delta I)_{P.P.} = -\mu_\kappa I \Delta x \qquad (8c)$$

where μ_τ, μ_σ , and μ_κ are the absorption coefficients for the photoelectric effect, the Compton effect and pair production, respectively. Adding all three together, we may write

$$(\Delta I) = (\Delta I)_{P.E.} + (\Delta I)_{C.E.} + (\Delta I)_{P.P.} = -(\mu_\tau + \mu_\sigma + \mu_\kappa) I \Delta x \qquad (9)$$

and comparing with Eq. 2, we get

$$\mu = \mu_\tau + \mu_\sigma + \mu_\kappa \qquad (10)$$

PHOTOELECTRIC EFFECT

The effect is more prominent at low energies of the incident photon. The incident photon is absorbed by one of the electrons of the atom. In the process the photon disappears and the electron is ejected with a kinetic energy K_e, given by

$$K_e = h\nu - I_B \qquad (11)$$

where $h\nu$ is the energy of the incident photon, and I_B is the binding energy of the orbital electron. In general, the cross section ($_a\tau$) of the photoelectric effect depends on Z and $h\nu$ in the following fashion

$$_a\tau \propto Z^5$$

$$\propto 1/\left(h\nu\right)^{7/2} \qquad (12)$$

COMPTON EFFECT

This is a process by which the incident photon interacts with a free electron and is scattered with a lower energy, the rest of the energy being taken by the recoiling electron. Because the electrons in an atom are loosely bound and the energies of the incident photons are comparatively high, we may include the scattering of photons by the electrons of the atom as Compton scattering.

An incident photon of energy $h\nu$ strikes a free electron with a rest mass m_0. The interaction results in a scattered photon of energy $h\nu'$ ($< h\nu$) at an angle θ and a recoiling electron with kinetic energy K_e at an angle ϕ.

COMPTON EFFECT

We can establish the following relations by using conservation of momentum and energy,

$$\lambda' - \lambda = \left(\frac{h}{m_0 c}\right)\left(1 - \cos\theta\right) \qquad (13)$$

$$h\nu' = \frac{h\nu}{1 + \alpha(1 - \cos\theta)} \qquad (14)$$

$$K_e = h\nu - h\nu' = h\nu\left(1 - \frac{1}{1 + \alpha\left(1 - \cos\theta\right)}\right) \qquad (15)$$

where $\alpha = h\nu / m_0 c^2$

PAIR PRODUCTION

The third most important process by which photons lose their energy is electron-positron pair formation. The threshold energy for this process is $2m_0c^2$.

It is found that if a photon of energy greater than 1.02 MeV strikes a foil of high Z, the photon disappears and in its place an electron-positron pair is formed. If a pair is produced in a cloud chamber and a magnetic field is applied, the electrons and the positrons are deflected in the opposite direction with equal curvature.

The conservation of momentum requires the presence of a heavy body. Actually the pair formation takes place in the field of the nucleus and the conservation of energy gives

$$h\nu = 2m_0c^2 + E_+ + E_- + E_{nuc} \qquad (16)$$

PAIR PRODUCTION

Where hν is the energy of the incident photon, $2m_0c^2$ is the energy equivalent to the rest mass of the electron and positron; E_+, E_- , and E_{nuc} are the kinetic energies of the positron, electron, and the recoiling nucleus, respectively. Because the mass of the nucleus is very large, it takes away a very small amount of kinetic energy, and so E_{nuc} may be neglected.

$$h\nu = 2m_0c^2 + E_+ + E_- \qquad (17)$$

The threshold for pair formation is $2m_0c^2$ or 1.02 MeV.

The process by which positrons are removed from circulation is called *pair annihilation*. When a positron is created, it has some kinetic energy that it loses by collisions with the atoms in its surroundings.

PAIR PRODUCTION

After it has slowed down considerably, it may form a kind of atom with one of the electrons of the medium. The so-called *positronium atom* is like a hydrogen atom, except a positron has replaced the proton. If the positronium atom formed is such that the spins of the electron and the positron are antiparallel, the atom disappears in a very short time ($\sim 10^{-10}$ sec), and it results in the creation of two photons. From conservation of energy and momentum,

$$2m_0c^2 = h\nu_1 + h\nu_2 \tag{18}$$

$$\frac{h\nu_1}{c} = \frac{h\nu_2}{c} \tag{19}$$

imply

$$h\nu_1 = h\nu_2 = 2m_0c^2 = 0.511\,MeV \tag{20}$$

Thus wherever there are positrons, the 0.511 MeV photons will be created in pairs and emitted in the opposite directions.

SUMMARY

The values of the atomic absorption cross-section $_a\tau$, $_a\sigma$, and $_a\kappa$ depend on the atomic number Z and the photon energy hν, approximately in the following way:

$$_a\tau \propto Z^5/\left(h\nu\right)^{7/2} \quad , \quad _a\sigma \propto Z/\left(h\nu\right)^a \quad , \quad _a\kappa \propto Z^2\left(h\nu\right)^b$$

Where a and b are positive numbers and have different values in different regions of photon energy. The total absorption coefficient per atom, $_a\mu$, is given by

$$_a\mu = {_a\tau} + {_a\sigma} + {_a\kappa}$$

The linear absorption coefficient is given by

$$\mu = \left(\rho N_A / A\right)\left[{_a\tau} + {_a\sigma} + {_a\kappa}\right]$$

and the mass absorption coefficient is given by

$$\mu/\rho = \left(N_A / A\right)\left[{_a\tau} + {_a\sigma} + {_a\kappa}\right]$$

MEASUREMENT OF GAMMA-RAY ENERGIES

- *Absorption method*

This method is based on the measurement of the absorption coefficient of an absorber by plotting intensity (count rate) versus thickness of the absorber. The measured absorption coefficient is compared with the theoretical values from which the energy of the γ-ray may be interpreted.

MEASUREMENT OF GAMMA-RAY ENERGIES

- Crystal-Diffraction Spectrometer

This method gives a direct measurement of the wave length. Because gamma rays are electromagnetic waves, it should be possible to diffract them.

Knowing the diffraction angle, θ , the wave length, λ , of the gamma ray may be calculated from Bragg's condition,

$$2d\sin\theta = n\lambda \qquad (21)$$

where d is the grating spacing, and n is the order of diffraction. Thus from λ , one can calculate the photon energy.

MEASUREMENT OF GAMMA-RAY ENERGIES

- Magnetic Spectrometer

When one or several groups of gamma rays of moderate energies (from ~ 1 MeV to ~ 3 MeV) are present, their accurate energy determination is made by using a magnetic spectrometer. Gamma rays are made to produce photoelectrons or Compton-recoil electrons, and the energies of these electrons are measured by means of a spectrometer. Knowing the maximum energy of the Compton electrons, the gamma-ray energies may be calculated by using Eq. 15. The maximum kinetic energy, K_m, is obtained from Eq. 15 by substituting $\theta=180^0$ (or $\phi=0$) in head on collision,

$$K_m = h\nu / \left(1 + m_0 c^2 / 2h\nu\right) \qquad (22)$$

or

$$h\nu = \frac{1}{2}\left[K_m + \left(K_m^2 + 2K_m m_0 c^2\right)^{1/2}\right] \qquad (23)$$

MEASUREMENT OF GAMMA-RAY ENERGIES

- Magnetic Spectrometer

The photoelectrons show up as spectral lines superimposed on the continuous Compton spectrum. Lines corresponding to the K-Shell and L-Shell electrons show up in most cases. Energies of these electrons can be calculated from the *Br* values. The energy of the gamma ray is given by

$$h\nu = K_e + I_B \tag{24}$$

MEASUREMENT OF GAMMA-RAY ENERGIES

- Scintillation Method

The use of a NaI(Tl) crystal is one of the simplest and most reliable methods for energy, as well as intensity, measurements of gamma rays from 50 keV to several MeV. Though the resolution is not high, it has a very high efficiency. The pulses produced are directly proportional to the energy deposited inside the crystal.

Compton distribution and photoelectric peaks also show up and are easily recognized.

INTERNAL CONVERSION

As mentioned in discussion of beta decay, there generally is a line spectrum superimposed on the continuous beta spectrum. These monoenergetic electrons are called conversion electrons, and the process by which they are emitted is called internal conversion.

The kinetic energy, K_e , of the conversion electrons is given by the formula

$$K_e = E_\gamma - I_B \qquad (25)$$

I_B represents the corresponding binding energy of the electron, and E_γ is the available energy for gamma emission by the nucleus.

THE AUGER EFFECT

The Auger effect is the emission of low-energy orbital electrons as an alternative to the emission of x-rays. There is always a vacancy created in the electronic shells by internal conversion, photoelectric effect, electron capture, or some other transitions.

This vacancy is filled by the transition of an electron from an outer orbit to the inner orbit, and the excited inner orbit gets rid of its energy either by emission of x-rays or by transferring its energy to the electron in a lower-energy shell. The electrons emitted by such a process are Auger electrons.

For example, if there is a vacancy in the K-shell, the transition of an electron from L-shell to K-shell will result in the excitation of the K-shell with energy equal to the difference in the binding energies of the K- and L- shells.

$$\Delta E = I_K - I_L \qquad (26)$$

THE AUGER EFFECT

The excited K-shell gets rid of its energy either by emitting a photon of energy $h\nu_{\kappa}$ given by $h\nu_{\kappa} = I_K - I_L$, where ν_{κ} is the frequency of the K x-ray or by emitting an L-Auger electron with a kinetic energy K_L given by

$$K_L = \Delta E - I_L = I_K - 2I_L \qquad (27)$$

INTERNAL PAIR PRODUCTION

Whenever gamma rays of energies, greater than 1.02 MeV interact with an absorber, electron-positron pairs are produced in the coulomb field of the nucleus. It has been shown that an excited nucleus with energy $>2m_0c^2$ may de-excite by a creation of an electron-positron pair somewhere in its own coulomb field.

Such a process is called internal pair-conversion and is an alternative to the γ-emission and conversion-electron emission. Again the process, just like γ-decay and conversion-electron process, is due to an electromagnetic interaction. The total available energy, E_0, for the transition is distributed as

$$E_0 = 2m_0c^2 + K_+ + K_- \qquad (28)$$

where K_+ and K_- are the kinetic energies of the positron and electron, respectively, and $2m_0c^2$ is the sum of the rest masses of the positron and the electron.

REFERENCES

1. Introductory Nuclear Physics. Kenneth S. Krane

2. Fundamentals of Nuclear Physics. Atam. P. Arya