Course Title

Course Code 102 / Department: PHYSICS

RADIATION AND PHOTONS

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RADIATION AND PHOTON

All the various forms of electromagnetic radiation, including light have a dual nature, they behave like waves when travelling through space but when interacting with atoms and molecules, they act like a stream of quantized energy or photon.

They energy E of each photon of frequency f and wavelength λ is given by $E = hf = \frac{hc}{\lambda}$ where

h=6.626 x 10^{-34} Js (Planck's Constant)

PHOTOELECTRIC EFFECT

When electromagnetic radiation is incident upon the surface of certain metals, electrons may be ejected. A photon of energy hf penetrates the material and is absorbed by an electron. If enough energy is available, the electron of the metal will be raised to the surface and ejected with some kinetic energy $\frac{1}{2} mv^2$. Let w be the energy required for an electron to break free of the surface, (work function). The maximum kinetic energy which the electron can have when it leaves the surface is therefore $E_{k,max} = hf - w$. This is called Einstein's Photoelectric equation.

The energy of the ejected electron may be found by determine what potential difference must be applied to stop its motion. Then for most energetic electron, $eV_s = hf - w$ where V_s is the stopping potential.

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The minimum frequency of light that will liberate electrons from the particular metal is known as threshold frequency. At this threshold frequency f_0, the photon delivers just enough energy to enable the electron to get out of the metal, with $E_k = 0$ $\therefore hf_0 = w$.

i.e. At the threshold frequency, the photon's energy just equals the work function.

The Momentum of a Photon

$E^2 = m^2c^4 + p^2c^2$, when m=0, E= pc

$$\therefore E = pc = hf \qquad\qquad \therefore p = \frac{hf}{c} = \frac{h}{\lambda}$$

$\therefore$ The momentum of a photon is $p = \frac{h}{\lambda}$

The Compton effect

Compton allowed a beam of monochromatic X-rays to fall on a scattering material, he observed that the scattered radiation have the same wavelength as the incident beam. But in addition Compton observed a scattered wavelength λ' greater than that of the original beam. The shift in wavelength $\Delta \lambda = \lambda' - \lambda$ was found to become larger as the scattering angle θ was increased. This scattering with an increase in wavelength is called the Compton effect. This effect is explained by photon picture of electromagnetic radiation. A photon can collide with a particle having mass

e.g. electron. When it does so, the scattered photon can have a new energy and momentum. Suppose a photon of initial wavelength λ collides with a free, stationary electron of mass Me and is deflected through an angle θ with a new scattered wavelength λ'. Then the scattered wavelength λ' is given by $\lambda' = \lambda + \frac{h}{m_e C}(1 - \cos\theta)$ which fits the experimentally measured wavelength shift as a function of scattering angle θ.

Example

Calculate the energy of a photon of blue light of wavelength 450nm

Solution

$$E = \frac{hc}{\lambda} = \frac{6.63 \times 10^{-34} J.s \times 2.998 \times 10^{8} m/s}{450 \times 10^{-9} m}$$

$$= 4.42 \times 10^{-19} J = 2.76 eV$$

Example 2

The work function of a group 1 metal is 2.3eV. What is the longest wavelength light that can cause photoelectron emission from this metal?

Solution:

At threshold, the photon energy equals the energy required to tear the electron loose from the metal. In other words, hf = w (i.e. the electron's K.E = 0) .: hf = w $\therefore w = \frac{hc}{\lambda}$

$$\therefore (2.3eV)\frac{(1.602 \times 10^{-19})}{1.00\ eV} = \frac{6.63 \times 10^{-34} J.s \times 2.998 \times 10^{8} m/s}{\lambda}$$

$$\lambda = 5.4 \times 10^{-7} m$$

Example 3

Calculate the work function of sodium metal if the photoelectric threshold wavelength is 680nm?

Solution

$$hf = w \qquad \therefore w = \frac{hc}{\lambda} \quad = \frac{6.63 \times 10^{-34} J.s \times 3 \times 10^{8} m/s}{680 \times 10^{-9} m}$$

$$\therefore w = \frac{6.63 \times 3 \times 10^{-26}}{6.8 \times 10^{-7}} = \frac{19.89 \times 10^{-26}}{6.80 \times 10^{-7}}$$

$$\therefore w = 2.925 \times 10^{-19} J.$$

In eV $\therefore w = \frac{2.925 \times 10^{-19}}{1.6 \times 10^{-19}} = 1.82 eV$

De Broglie Wavelength

A particle of mass m in moving with momentum p has associated with it a de Broglie wavelength given by $\lambda = \frac{h}{p} = \frac{h}{mv}$. A beam of particles can undergo both diffraction and interference phenomenon. These wavelike properties of particles can be computed by assuming the particles to behave like wave (de Broglie waves) having the de Broglie wavelength.

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RADIOACTIVITY

Radioactivity is defined as the spontaneous disintegration of unstable nuclei: Nuclei found in nature with atomic number Z greater than that of lead, (Z = 82) are unstable or radioactive. A radioactive nucleus spontaneously ejects one or more particles in the process of transforming into a different nucleus. Early result on radioactive materials shown that they emit three kind of rays. These are α, β, and γ ray. Later experiments on radioactive material showed α rays to be positively charged helium atoms, β rays to be electrons and gamma (γ) rays to be electromagnetic radiation of short wavelength.

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STATISTICAL LAW OF RADIOACTIVE DECAY

The activity of a radioactive sample (i.e the number of distingerations per second) is an experimental (or logarithmic) function of time. This means that the activity decreases with time.

A simple relation that exists between the number N of atoms of radioactive material present and the number ΔN that will decay in a short time Δt is given by $\Delta N = \lambda N \Delta t$ where λ is called the distingeration /decay constant. It represents the fractional number of radioactive atoms decaying per unit time.

$$\lambda = \frac{\Delta N}{N \triangle t}$$

One can express the number N of radioactive atoms remaining after time t in time of number N_0 originally present at time t = 0 as: $N = N_0 e^{-\lambda t}$

The time at which the number of radioactive atoms remaining is just one-half the original number is called the half-life ($t½$). it is related to decay constant through $\lambda t½ = 0.693$

Note $\frac{N}{N_0} = \frac{1}{2} = e^{-\lambda t\frac{1}{2}}$ $\therefore t\frac{1}{2} = \frac{ln2}{\lambda} = \frac{0.693}{\lambda}$. λ has a unit of S^{-1}

$\frac{\Delta N}{\Delta t}$ is the rate of distingerations (activity of the sample) and it is equal to λN. The S.1 unit of activity is the Becquerel (B_q) where $1B_q = 1$ decay/s

GAMMA DECAY

A nucleus in an excited state ${}^{A}_{z}\overset{*}{X}$ may go to a state of lower energy by emitting the difference in energy as a photon.

i.e ${}^{A}_{z}\overset{*}{X} \rightarrow {}^{A}_{z}X + hv$

the gamma (γ) decay does not cause a charge in the atomic number or the mass number of the nucleus.

Note: Study of γ radiation gives important information about the initial and final states of the nucleus undergoing a γ transition. The observed energies of emitted photons give consistent results for the nuclear energy levels as $h\nu = E_i - E_f$.

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ALPHA DECAY

When an α particle is ejected from the nucleus, the original nucleus loses 2 protons and 2 neutrons. Its mass number decreases by 4 unit while its atomic number decreases by 2.

i.e. ${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He + Q$. Where Q is the distingeration energy.

$$Q = E_{k,d} + E_{k,\propto} = (m_p - m_d - m_{\propto})c^2$$

Example 1: Find the Q value for the distingeration of ${}^{144}_{60}N \rightarrow {}^{4}_{2}He + {}^{140}_{58}Ce$

Solution:

from tables of isotope masses ${}^{4}_{2}He = 4.00387,\ \ {}^{140}_{58}Ce = 139.94977\ and\ {}^{144}_{60}Ne = 143.95556$

$$\therefore\ \ m = 143.95556 - (4.00387 + 139.94977)$$

$$\therefore\ \ m = 143.95556 - 143.95364 = 0.00192$$

$$\therefore\ \ Q = mc^2 = 0.00192c^2 = 1.79MeV$$

BETA DECAY

There are high energy electrons that are created by a rearrangement of the original nucleus into a state of lower energy. There are two different types of β- decay: (a) β^- decay, in which an electron is emitted from the nucleus and β^+ decay, in which a positron is emitted.

$$ {}_{Z}^{A}X \rightarrow {}_{Z+1}^{A}Y + {}_{-1}^{0}e + Q $$

$$ {}_{Z}^{A}X \rightarrow {}_{Z+1}^{A}Y + {}_{+1}^{0}e + Q $$

For β^- decay to occur, the mass of the decaying nucleus must be greater than the mess of the product nucleus plus the mass of an electron. The condition for β^+ decay is slightly more complicated where $Q = (m_x - m_y - 2me)\, c^2$ where m_e is the rest mass of an electron.

NUCLEAR REACTIONS

We may consider a general notation for a nuclear reaction in which a particle or nucleus x strikes a nucleus X and results in the emission of particle y, leaving a nucleus Y.

$X + x \rightarrow Y + y$ The notation is often abbreviated as X (x,y) Y where X is the struck nucleus, (x, y) stand for the incoming and outgoing particles respectively and Y represents the residual nucleus. For example, the nuclear reaction

$$^{14}_{7}N + ^{1}_{1}H \rightarrow ^{11}_{6}C + ^{4}_{2}He$$

can be written according to the notation above as $^{14}_{7}N + ^{1}_{1}H \rightarrow ^{11}_{6}C + ^{4}_{2}He$ or ^{14}N(p, α) ^{11}C

others are $^{27}_{13}Al + ^{1}_{0}n \rightarrow ^{27}_{12}Mg + ^{1}_{1}H$ or ^{27}Al (n, p) ^{27}Mg

$^{10}B + ^{1}_{0}n \rightarrow ^{7}_{3}Li + ^{4}_{2}He$ or ^{10}B (n, α) ^{7}Li

Example

The half-life of radon is 3.80 days. After how many days will only one – sixteenth of a radon sample remain?

Solution

Using $\lambda = \frac{ln2}{t_{\frac{1}{2}}} = \frac{0.693}{3.80d} = 0.182/d$

$$\therefore {}^{N}/_{N_0} = \frac{1}{16} = e^{-\lambda t} = e^{-0182/dt} = e^{-0.182t}$$

$$\therefore -0.182t = \ell\text{n}\left(\frac{1}{16}\right) = -2.77$$

$$\therefore t = 15.2d$$

Example 2: Find the activity of a 1g sample of radium ($^{226}_{88}Ra$) whose half-life is 1620 years.

Solution: $\lambda = \frac{0.693}{1620yrs} = 4.28 \times 10^{-4}/yr = 1.36 \times 10^{-11}/s$

1 gram of ^{226}Ra contains a number of atoms equal to

$$N = \frac{6.025 \times 10^{23} atom\ per\ mole\ \times 1.0g}{226g/mole} = 2.7 \times 10^{21} atoms$$

Hence Activity = λN

= $(1.36 \times 10^{-11}/s) \times (2.7 \times 10^{21}$ atoms)

= 3.6×10^{10} distingerations per second

= $3.6 \times 10^{10} S^{-1}$

= 0.97 Ci

Note: 1 Curie = 3.7×10^{10} distingerations/S

$1ci = 3.7 \times 10^{10}$ distingeration/s

$x = 3.6 \times 10^{10}$

$= 0.97C_1$