RADIOACTIVITY

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RADIOACTIVITY

Most of our knowledge about the physics of atom and its nucleus started with the discovery of radioactivity by Henri Becquerel in 1896.

The radioactive decay of naturally occurring minerals containing uranium and thorium are in large part responsible for the birth of the study of nuclear physics.

In addition to this naturally occurring radioactivity, we also have the capability to produce radioactive nuclei in the laboratory through nuclear reactions.

Joliot-Curie team was awarded the 1935 Nobel Prize in Chemistry for the work on artificially produced radioactivity.

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ALPHA PARTICLES: Alpha particles always ionize the gas through which they travel and in the process of ionization, they lose energy and velocity. The ranges of alpha particles in matter are quite limited and the value of the range of alpha particles in the air varies from 2 cm to 10 cm. Alpha particles produce a dense, nearly linear ionization track (high LET (Linear Energy Transfer (LET)) radiations)

BETA PARTICLES: Beta particles cause much less ionization than alpha particles, but are ~100 times more penetrating. Beta particles are not stopped by a thin sheet of paper, but a thin foil of aluminum does stop a large fraction of them.

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GAMMA-RAYS: Gamma rays also cause ionization of a gas, but to a lesser degree than that caused by α or β particles. The penetrating power of γ rays is ~100 times greater than that of β particles. γ rays are not stopped by many centimeters of aluminum, but a few centimeters of lead can stop a large fraction of them. Because they carry no charge, they are not deflected by electric or magnetic fields, and they exhibit all the characteristics of electromagnetic waves.

(See Figure 2.1, Fundamentals of Nuclear Physics, by Atam P. Arya)

THE RADIOACTIVE DECAY LAW

Radioactive decay is the process in which an unstable nucleus spontaneously loses energy by emitting ionizing particles and radiation. This decay, or loss of energy, results in an atom of one type, called the parent nuclide, transforming to an atom of a different type, named the daughter nuclide. The three principal modes of decay are called the alpha, beta and gamma decays.

Experimental evidence shows that radioactive decay follows an exponential law. It is possible to derive this law, if it is assumed that the decay is statistical in nature.

This statistical nature implies that it is not possible to predict which atom will decay in the next second.

THE RADIOACTIVE DECAY LAW

Let us assume that each undecayed nucleus (or sometimes we shall use the term ‘undecayed atom’) has a probability λ that it will decay in the next second (assuming that $\lambda \ll 1$). In time *dt* the probability of decay of each atom will be λdt.

If there are N undecayed atoms at a given time, the number, dN, that will decay in the short time, dt, is given by

$$dN = -\lambda dt N$$

$$\frac{dN}{N} = -\lambda dt$$

Assuming that at time $t=0$, the number of radioactive atoms present is N_0

THE RADIOACTIVE DECAY LAW

It leads to the exponential law of radioactive decay:

$$N(t) = N_0 e^{-\lambda t} \qquad (1)$$

where *N(t)* is the number of radioactive atoms present at time t. The constant of proportionality λ is called the disintegration or decay constant.

$$\lambda = -\frac{dN/dt}{N}$$

in which λ is the probability per unit time for the decay of an atom. The basic assumption of the statistical theory of radioactive decay is that λ is independent of time and of the number and type of other nuclei present.

THE RADIOACTIVE DECAY LAW

The activity is defined as the number of disintegrations per second that result from a given sample. From

$$N(t) = N_0 e^{-\lambda t}$$

we find

$$Activity = \left| \frac{dN(t)}{dt} \right| = \lambda N_0 e^{-\lambda dt} = \lambda N \qquad (2)$$

Thus, the activity of a sample depends on the actual number, N, of radioactive atoms present and the decay constant, λ.

THE RADIOACTIVE DECAY LAW

Another quantity of importance in radioactivity is half-life, denoted by $t_{1/2}$. It is defined as the time interval in which the activity decreases by one half. Because the activity is proportional to the number of undecayed atoms present, $t_{1/2}$ is also equal to the time interval during which the number of undecayed atoms decreases by one-half.

Substitution of $N=N_0/2$ and $t= t_{1/2}$ in

$$N(t) = N_0 e^{-\lambda t}$$

yields,

$$\frac{N_0}{2} = N_0 e^{-\lambda t_{1/2}} \quad or \quad t_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda} \qquad (3)$$

THE RADIOACTIVE DECAY LAW

The exponential form of the decay makes it evident that it will take infinite time for the complete disappearance of radioactive atoms. We do not know, of course, which atom is going to decay next, and individual atoms may have lifetimes anywhere from zero to infinity. For the statistical nature of this phenomenon, we must define the quantity average or mean lifetime, τ.

$$\tau = \frac{1}{\lambda} \qquad (4)$$

Thus the mean lifetime is simply the inverse of the decay constant.

τ is also defined as the average time that a nucleus is likely to survive before it decays.

THE RADIOACTIVE DECAY LAW

The average life, τ, of a radioactive nucleus can be calculated by summing the lives of all the nuclei and dividing by the total number of nuclei. Suppose dN_1 nuclei have a lifetime t_1, that dN_2 have t_2 , that dN_3 have t_3, and so on. The mean life therefore,

$$\tau = \frac{t_1 dN_1 + t_2 dN_2 + t_3 dN_3 + \ldots}{dN_1 + dN_2 + dN_3 + ..} = \frac{\int_0^{N_0} t\, dN}{\int_0^{N_0} dN} = \frac{\int_0^{N_0} t\, dN}{N_0}$$

Where, $N_0 = dN_1 + dN_2 + dN_3 + \ldots$

$$\tau = \frac{-\int_{\infty}^{0} \lambda t\, N_0 e^{-\lambda t} dt}{N_0} = \int_0^{\infty} \lambda t\, e^{-\lambda t}\, dt = \frac{1}{\lambda}$$

PRODUCTION AND DECAY OF RADIOACTIVITY

In many applications, we produce activity continuously, such as by a nuclear reaction.

Let's assume that we place a target of stable nuclei into a reactor or an accelerator such a cyclotron. The nuclei of the target will capture a neutron or a charged particle, possibly leading to the production of a radioactive species.

The rate R at which this occurs will depend on the number N_0 of target atoms present, on the flux or current I of incident particles, and on the reaction cross section σ (which measures the probability for one incident particle to react with one target nucleus).

$\sigma \rightarrow$ in the barn unit (10^{-24} cm^2)

A typical flux of particles in a reactor or cyclotron $\rightarrow$ 10^{14} /s.cm^2

PRODUCTION AND DECAY OF RADIOACTIVITY

Even if the reaction is allowed to continue for hours, the absolute number of converted target particles is small. We can therefore, to a very good approximation, regard the number of target nuclei as constant, and under this approximation the rate R is constant. As we ‘burn up’ target nuclei, N_0 will decrease by a small amount and the rate may therefore similarly decrease with time. Obviously,

$$N_0 \; must \; go \; to \; zero \; as \quad t \to \infty$$

Thus,

$$R = N_0 \sigma I \qquad (5)$$

Let's donate by N_1 the number of radioactive nuclei that are formed as a result of the reaction.

PRODUCTION AND DECAY OF RADIOACTIVITY

These nuclei decay with decay constant λ_1 to the stable nuclei denoted by N_2. Thus, the number of nuclei N_1 present increases owing to the production at the rate R and decreases owing to the radioactive decay:

$$dN_1 = Rdt - \lambda_1 N_1 dt$$

$$N_1(t) = \frac{R}{\lambda_1}\left(1 - e^{-\lambda_1 t}\right)$$

and the solution to this equation is easily obtained

$$A_1(t) = \lambda_1 N_1(t) = R\left(1 - e^{-\lambda_1 t}\right)$$

PRODUCTION AND DECAY OF RADIOACTIVITY

If the irradiation time is short compared with one half-life, then we can expand the exponential and keep only the term linear in t:

$$A_1(t) \cong R\lambda_1 t \qquad t \ll t_{1/2}$$

For small times, the activity thus increases at a constant rate. This corresponds to linear accumulation of product nuclei, whose number is not yet seriously depleted by radioactive decays.

For times long compared with the half-life the exponential approaches zero and the activity is approximately constant:

$$A_1(t) \cong R \qquad t \gg t_{1/2}$$

In this case new activity is being formed at the same rate at which the older activity decays.

UNITS OF RADIOACTIVITY

A frequently used unit of activity is the **Curie** (Ci), defined as,

$$1\,Ci = 3.7x10^{10}\ decays/s$$

This value was originally selected because it is the approximate activity of 1 g of radium. The half-life radium is 1620 years and the decay constant,

$$\lambda_{radium} = \frac{0.693}{1.62x10^{3}\ yrs} = 13.8x10^{-12}\ \sec^{-1}$$

The mass of radium is 226 amu and there are $6.02x10^{23}$ atoms in one gram-atom of radium, therefore, one gram of radium contains,

$$\frac{1gr\ x\ 6.02x10^{23}\ atoms}{2.26x10^{2}\ gr} = 2.66x10^{21}\ atoms$$

UNITS OF RADIOACTIVITY

Hence, the disintegration rate is

$$\frac{dN}{dt} = \left|\lambda N\right| = 13.8x10^{-12}\ x\ 2.66x10^{21} \cong 3.7x10^{10}\ di\sin tegrations/s\text{ec}$$

The SI unit of activity is the **becquerel** (Bq):

$$1\,Bq = 1\,decay/s$$

Therefore, 1 Ci = 3.7 x 10^{10} Bq. The curie is a rather large unit, and the more frequently used activity units are the millicurie and the microcurie.

REFERENCES

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