Production and Applications of Radioisotopes

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Abstract

Over the last century, nuclear science and technology have contributed immensely to almost every social and economical sector and in virtually every corner of globe. Radioisotope is one of the tools for studying nuclear science. The radioisotopes have numerous applications in medicine, agriculture, industry and pure research. Production and some applications of radioisotopes are discussed briefly.

Keywords: Radioisotopes; tracer technique; cyclotron; nuclear reactor.

1. Introduction

In nature there are nearly 300 nuclei, consisting of different elements and their isotopes. Isotopes are nuclei having the same number of protons but different number of neutrons. They are elements having the same atomic number but different mass numbers. The unstable nuclei decay by emission of α or β particles or γ radiation. Some very heavy nuclei decay also by fission. Such isotopes, which emit radiation, are called radioisotopes.1,2 Most of the radionuclides found in nature are members of four radioactive series (Table.1), with each series consisting of a succession of daughter products all ultimately derived from a single parent nuclide. The nuclides in each chain decay by emitting α and/or β particles until a final (stable) nuclide is reached.

Radioisotopes, because of their radiation characteristics and the energy they possess, can be utilized in industry, agriculture, healthcare and research applications. While natural radioactivity is common in heavy elements, it is rather rare in light elements exception being 40K, 87Rb, 51V, etc. But, radioactivity can be induced in light elements by suppling them with excess energy. This can be brought about by exposing the
element to neutrons in a nuclear reactor or to charged particles like proton, deuteron or alpha particle in a cyclotron. More than 1600 radioisotopes have been identified which can be produced either in a reactor or in a cyclotron.

India is a leading producer of radioisotopes in the world. Production of radio-isotopes in the country had started with the commissioning of first research reactor named “APSARA” (Swimming Pool type 1 MW (th) Power) in 1956. The production capability was augmented in 1963 when the reactor CIRUS attained its full rated capacity of (40 MW (th)). There was a major increase in the production capacity when the reactor DHRUVA (100 MW (th)) commissioned in 1985 at Trombay (Maharashtra). Radioisotopes are also produced using accelerator at Variable Energy Cyclotron Centre (VECC), Kolkata. DHRUVA, CIRCUS and APSARA have been used for production of radioisotopes besides their use in basic and applied research, irradiation testing of fuels, materials and training.

<table>
<thead>
<tr>
<th>Mass numbers</th>
<th>Series</th>
<th>Parent</th>
<th>Stable end product</th>
</tr>
</thead>
<tbody>
<tr>
<td>4n</td>
<td>Thorium</td>
<td>$^{90}\text{Th}$</td>
<td>$^{208}\text{Pb}$</td>
</tr>
<tr>
<td>4n + 1</td>
<td>Neptunium</td>
<td>$^{93}\text{Np}$</td>
<td>$^{209}\text{Bi}$</td>
</tr>
<tr>
<td>4n + 2</td>
<td>Uranium</td>
<td>$^{92}\text{U}$</td>
<td>$^{206}\text{Pb}$</td>
</tr>
<tr>
<td>4n + 3</td>
<td>Actinium</td>
<td>$^{92}\text{U}$</td>
<td>$^{207}\text{Pb}$</td>
</tr>
</tbody>
</table>

2. Production of Radioisotopes in a Research Reactor

Radioisotopes are produced in a nuclear reactor$^{1,2}$ by exposing appropriate target material to the neutrons in the reactor, thereby causing a nuclear reaction to occur which leads to the production of desired radioisotope. The factors which decide the type of nuclear reaction that takes place and the rate of production are:

1. The energy of the neutrons and the neutron flux.
2. The characteristics and quantity of the target material.
3. The activation cross-section for the desired reaction.

Neutron flux is the product of neutron density and the average speed of the neutron and is expressed as $n/\text{cm}^2/\text{sec}$. The neutron interaction with the nucleus of the target material can be expressed quantitatively in terms of nuclear cross section. It is a measure of the probability that a given nuclear reaction takes place. This can be expressed in terms of an imaginary cross-sectional area presented by nucleus around the nucleus to the beam of neutrons, perpendicular to the beam such that if and only if the neutrons pass through this area, the nuclear reaction takes place. The value of the cross-section varies with the energy of the interacting neutrons and from nucleus to nucleus. The maximum value of the cross-section is for thermal neutrons. Higher the cross-section; higher the probability of radioisotope formation.

Characteristics of the Target Material

(i) Substances which are explosive, pyrophoric, volatile, etc. are not permitted to be irradiated in reactor.
(ii) Targets should be stable under irradiation conditions.
(iii) Isotopically pure target gives high specific activity radioisotopes.
(iv) The physical form of the target should be such that the neutron flux depression is minimum.
(v) The target should be in a suitable chemical form for post irradiation processing. Usually target in metallic form or oxides are preferred.
(vi) If the target is hygroscopic, it is preferable to preheat the target prior to encapsulation.

Nuclear reactions leading to radioisotope production\textsuperscript{1,2} are:

(i) (n,\(\gamma\)) reaction: Radiative capture
This is primarily a thermal neutron reaction
\[ \frac{59}{27}\text{Co} + \frac{1}{0}n \rightarrow \frac{60}{27}\text{Co} + \gamma \quad (\sigma = 36b) \]
\[ \frac{98}{42}\text{Mo} + \frac{1}{0}n \rightarrow \frac{99}{42}\text{Mo} + \gamma \quad (\sigma = 0.12b) \]
Here, the product is an isotope of the target element itself and hence cannot be chemically separated.

(ii) (n,\(\gamma\)) followed by \(\beta^-\) decay:
In some cases (n, \(\gamma\)) reaction leads to a product with short half-life which decays by \(\beta^-\) emission to the isotope of interest.
\[ \frac{130}{52}\text{Te} + \frac{1}{0}n \rightarrow \frac{131}{52}\text{Te} \rightarrow \frac{131}{53}\text{I} + \gamma \]
Chemical separation of I from the target material tellurium is possible.

(iii) (n, p) reaction
\[ \frac{32}{16}\text{S} + \frac{1}{0}n \rightarrow \frac{33}{15}\text{P} + \frac{1}{1}\text{H} \]
\[ \frac{59}{28}\text{Ni} + \frac{1}{0}n \rightarrow \frac{60}{27}\text{Co} + \frac{1}{1}\text{H} \]

(iv) (n, a) reaction
\[ \frac{6}{3}\text{Li} + \frac{1}{0}n \rightarrow \frac{3}{1}\text{H} + \frac{4}{2}\text{He} \]

(v) Multistage reactions
\[ ^{238}\text{U}(n,\gamma) \rightarrow ^{239}\text{U} \rightarrow ^{239}\text{Np} \rightarrow ^{239}\text{Pu} \]

(vi) Fission reaction
Fission of uranium atom \(^{235}\text{U}\) by thermal neutron leads to the formation of a number of radioisotopes. Each fission provides two fission fragments, light (mass no around 95) and heavy (mass no around 140), with the release of about 2.4 neutrons/fission. In fact the nuclear reactors work on the principle of controlled nuclear fission.

Calculation
When a target is undergoing irradiation in a reactor, a nuclear reaction takes place leading to the production of radioisotope. The activation per second (the rate of production) can be written as,
\[ \frac{dN_1}{dt} = \phi \sigma_{\text{act}} N_T, \quad (1) \]
where \(N_T\) = Total number of atoms present in the target
\(\phi\) = Neutron flux in \(n/cm^2/s\)
\(\sigma_{\text{act}}\) = Activation cross section
\(N_1\) = Number of activated atoms at an instant of time.

Thus, the rate of production is independent of time.\textsuperscript{1} Once the radioisotope is produced, it starts decaying with its own half-life. The net rate of increase of radioactive nuclei (decay constant \(\lambda\)) is the difference between the rate of production and the rate of decay.
\[ \frac{dN_1}{dt} = \phi \sigma_{\text{act}} N_T - \lambda N_1 \quad (2) \]
or
\[ \frac{dN_1}{dt} + \lambda N_1 = \phi \sigma_{\text{act}} N_T \quad (3) \]
The solution of equation (3) gives,
The activity of the sample is defined as

$$N_1 = \frac{\phi \sigma_{act} N_f}{\lambda} (1-e^{-\lambda t})$$  \hspace{1cm} (4)$$

where $t$ = time of irradiation in seconds.

Equation (5) shows that the growth of activity in a target under irradiation is exponential and reaches a saturation value limited by the neutron flux in the reactor.

$$\text{activity} = \lambda N_1 = \phi \sigma_{act} N_f (1-e^{-\lambda t})$$  \hspace{1cm} (5)$$

3. Production of certain Medical Isotopes:

(a) IODINE – 131: This isotope is used in the diagnosis and treatment of thyroid disorders. It is obtained by the irradiation of natural Te in the reactor.\textsuperscript{1} - \textsuperscript{4}

$$^{130}\text{Te} + \gamma \rightarrow ^{131}\text{Te} \rightarrow ^{131}\text{I} + \gamma$$

A wet process of oxidation with H$_2$CrO$_4$ + H$_2$SO$_4$ mixture followed by reduction with oxalic acid is utilized for the preparation of this isotope from the target.\textsuperscript{131}I released is absorbed in Na$_2$SO$_3$ solution and supplied as Na$^{131}$I in alkaline sulphate solution. This is produced on a weekly basis and is in good demand for use as diagnostic and therapeutic agent for thyroid disorders.

(b) Phosphorous – 32: This isotope is used in bone metastasis to control the pain, in agriculture and synthesis of nucleotides. This is obtained by the neutron irradiation of natural sulphur. Sulphur, after irradiation is distilled under vacuum to leave phosphorous in the flask. This phosphorous is leached with dil. HCl and then purified for removal of cationic impurities by passage through Dowex 50x 8. The product $^{32}$P is supplied as H$_3$PO$_4$ solution (Ortho phosphoric acid). Normally about 2-3 Ci $^{32}$P is produced fortnightly from 200g Sulphur depending on the time of irradiation, flux etc. In terms of weight about 10-15 μg of phosphorous is separated from bulk of sulphur.

(c) Chromium – 51: This isotope is produced in the reactor by Szilard-Chalmer’s process during the irradiation of potassium chromate. The difference in the valency state of $^{51}$Cr produced (+3) is utilized in effecting a chemical separation of the product from the target material.

4. Cyclotron Produced Isotopes

Cyclotron was devised by Lawrence and Livingston in 1932\textsuperscript{1,3,4} to accelerate charged particles like protons, deuterons and alpha. These particles are accelerated to high energy levels and are allowed to impinge on the target material. $^{11}$C, $^{13}$N, $^{18}$F, $^{123}$I etc. are some of the isotopes that can be produced in a cyclotron given in Table 2.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>T$_{1/2}$</th>
<th>Target</th>
<th>Reaction</th>
</tr>
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<tbody>
<tr>
<td>$^{18}$F</td>
<td>110 min</td>
<td>H$_2$O</td>
<td>$^{18}$O(p, n) $^{18}$F</td>
</tr>
<tr>
<td>$^{11}$C</td>
<td>20 min</td>
<td>N$_2$</td>
<td>$^{14}$N(p,α) $^{11}$C</td>
</tr>
<tr>
<td>$^{15}$N</td>
<td>10 min</td>
<td>H$_2$O</td>
<td>$^{16}$O(p,α) $^{13}$N</td>
</tr>
<tr>
<td>$^{15}$O</td>
<td>2 min</td>
<td>N$_2$</td>
<td>$^{14}$N(d, n) $^{15}$O</td>
</tr>
<tr>
<td>$^{67}$Ga</td>
<td>78 h</td>
<td>$^{65}$Zn, $^{67}$Cu</td>
<td>$^{68}$Zn(p, 2n) $^{67}$Ga, $^{68}$Cu(α, 2n) $^{67}$Ga</td>
</tr>
</tbody>
</table>
5. Applications of Radioisotopes

The radioisotopes\(^{5-8}\) have numerous applications in medicine, agriculture, industry and pure research. Many applications employ a special technique known as “tracer technique”.\(^{3,4}\) A small quantity of a radioisotope is introduced into the substance to be studied and its path is traced by means of a Geiger-Muller (G. M.) counter.\(^{3,4}\)

**Medical Uses** – Radioisotopes and their formulations find varied applications in diagnosis, therapy and healthcare. Bhabha Atomic Research Centre (BARC) supplies reactor produced radioisotopes and radionuclides for medical use. The radioisotopes processed and supplied by Board of Radiation & Isotope Technology (BRIT), Mumbai to medical uses across the country, include radiopharmaceuticals, brachy-therapy wires, radio-immunoassay (RIA) kits and various other products, and services. The accelerator at VECC manufactures radioisotopes, which are processed for medical applications. The Regional Radiation Medicine Centre (RRMC) meets the requirements of the eastern region of the country, for radiodiagnosis and therapy.

The radiations given out by some radioisotopes are very effective in curing certain diseases. For example, radio-cobalt (\(^{60}\)Co) is used in the treatment of brain tumour, radio-phosphorous (\(^{32}\)P) in bone diseases and radio-iodine (\(^{131}\)I) in thyroid cancer. The radiations, besides destroying the ailing tissue, also damage the healthy tissue and hence a careful control over the quantity administered is necessary. Bacteria and other disease-carrying organisms can be destroyed by irradiating them with \(^{\gamma}\)-rays. The process is used to sterilise medical instruments, plastic hypodermic needles, packets of antibiotics, and hospital blankets; whereas heat sterilisation would damage them. A portable source of \(^{\gamma}\)-rays for sterilization is radio-cobalt (\(^{60}\)Co). X-ray photography in medical diagnosis can be replaced by \(^{\gamma}\)-ray photography with advantage. The \(^{\gamma}\)-ray source (radioisotope) is compact and needs no power supply.

In the field of medicine the tracer technique is employed in a number of ways. For example, the doctor can find out any obstruction in the circulation of the blood in the human body. He injects radio-phosphorous (\(^{32}\)P) into the blood of the patient and examines the movement of the blood by detecting radiations emitted by \(^{32}\)P by means of G. M. counter. He can thus locate clots of blood present in the body. In a similar way, the passage of a particular element in the body and the rate at which it accumulates in different organs can be studied. For example, phosphorous accumulates in bones, and iodine in thyroid gland.

**Agricultural Uses** – Radiations from certain radioisotopes are used for killing insects which damage the food grains. Certain seeds and canned food can be stored for longer periods by gently exposing them to radiations. Better yields of milk from cows, and more eggs from hens have been obtained on the basis of information gained by mixing radioisotopes with their diet. Radioisotopes are used for determining the function of fertilizer in different plants. Radioisotopes are also used for producing high yielding crop seeds. Thus the agricultural yield is increased. The research at Trombay in the field of crop development has led to the development of 23 high yielding varieties of pulses, oilseeds, rice and jute. The BARC has developed groundnut varieties, which are very popular amongst farmers. BARC has also developed a tissue culture based protocol for rapid multiplication of 12 commercial cultivators of banana.

In agriculture, the tracer technique is used to study the rate and direction of movement of an element in a plant. For this a radioisotope of that element is injected in the…
ground near the plant. After a few days the plant is laid on a photographic paper to produce an autoradiograph. The dark areas in the radiograph show the positions reached by the element. This technique gives valuable information regarding the optimum season for fertilising crops and for poisoning weeds.

**Industrial Uses** – There are many different uses to which radioisotopes are put in industry. These include radiography, gamma scanning of process equipment, use of radiotracers to study sediment transport at ports and harbours, flow measurements, hydrology and water resource management. The isotope related services like sediment transportation, gamma scanning leakage detection and others have led to considerable monetary savings to the nation. By $\gamma$-ray photography we can find out wearing of cutting tools and lathes and can locate internal cracks in stones. We can check any non-uniformity in the thickness of a sheet by $\beta$ or $\gamma$-absorption measurements. The sheet is made to run continuously between a radioisotope (emitting $\beta$ or $\gamma$-rays) and a counter. A change in the counting rate indicates a variation in the thickness of the sheet. The output from the counter may be used to correct the machinery, which is rolling the sheet as soon as a variation is detected, and thus the thickness is automatically kept constant. This method is used as a thickness control in the manufacture of paper, plastic, metal sheet, etc. The same method can be used to check sealed cigarette packets whether they are full or if one or more cigarette is missing. The packets are placed on a conveyor belt running between a radioisotope and a counter. An empty or partially filled packet gives a higher counting rate due to less absorption of radiation than with a completely filled packet. The increase in counting rate can be converted into an electronic signal which knocks the incomplete packet off the belt.

In *industry*, the tracer technique is used for testing the uniformity of mixtures. For testing a chocolate mixture, a small quantity of short-lived radioisotopes such as $^{24}$Na or $^{56}$Mn is added to the primary ingredients. Several different samples of the final products are then tested for radioactivity by means of a G. M. counter. If each sample gives the same counting rate, then the mixing has been uniform. This method can be used in mixing processes occurring in the manufacture of chocolate, soap, cement paints, fertilizers, cattle food and medical tablets. The tracer technique is extremely sensitive in testing the *sealing process* in making envelopes for radio valves. A sample valve is filled with radio-krypton ($^{85}$Kr) and a G. M. counter is held outside the valve. The counter detects even an extremely poor leakage.

6. **Conclusion**

Radioisotopes have numerical applications in medicine, agriculture, industry and pure research. Many applications employ a special technique known as “tracer technique”. It is felt that in addition to the marathon efforts of scientists and engineers engaged in developing nuclear science and technology the sincere efforts of media in popularizing and propagating the beneficial uses of radioisotopes for national development are going to play a major role in realizing the full potential of atom.

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