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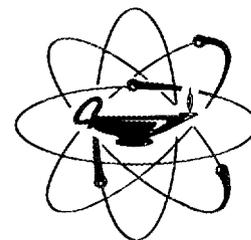
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## ISOTOPE USER'S GUIDE

F. E. McKinney  
S. A. Reynolds  
P. S. Baker

ISOTOPES INFORMATION CENTER



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F. E. McKinney  
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SEPTEMBER 1969

**OAK RIDGE NATIONAL LABORATORY**  
Oak Ridge, Tennessee  
operated by  
**UNION CARBIDE CORPORATION**  
for the  
**U. S. ATOMIC ENERGY COMMISSION**



## FOREWORD

This guide has been prepared to help the user of isotopes choose the best one for his purpose. For many years the Oak Ridge National Laboratory isotope catalog was distributed to high school, college, and university students to supply the various kinds of information concerning radioisotopes. Since a great deal of the catalog material had to do with availability (i.e., it was a sales catalog), much of the information was useless as far as the students were concerned; hence it seemed appropriate to excerpt the supplementary information from the catalog, to add additional data that would be appropriate to the above-mentioned audience, and to publish it as a separate document. It is with this in mind that the Isotope User's Guide has been written.

The Guide is a product of Oak Ridge National Laboratory's Isotopes Information Center. The Center, formally announced in March 1966, was established under the sponsorship of the U.S. Atomic Energy Commission to collect, evaluate, and disseminate worldwide information primarily on production and uses of radioisotopes in industry and research. The technical staff of the Center scans many types of literature to locate information that is within the Center's scope. In-scope reports, journal articles, books, and bibliographies are obtained, read, analyzed, and indexed. Over 700 key words are used in indexing.

The Center attempts to answer, without charge, all reasonable questions within its capabilities. Other ways in which the Center makes information available include:

- Preparation of *Isotopes and Radiation Technology*, a quarterly Technical Progress Review that emphasizes isotope applications. This review may be obtained from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, for \$2.50 per year or 70¢ per issue.
- Issuance of state-of-the-art reviews and special bibliographies on various areas of isotope applications.
- Written critical evaluations of various fields of isotope use and production, with particular attention to the worldwide situation.
- Special educational and promotional materials (i.e., this document) such as talks, exhibits, brochures, and pamphlets used in various parts of the AEC program.

Requests for information or inquiries concerning the operation of the Center may be addressed to:

P. S. Baker, Director  
Isotopes Information Center  
Oak Ridge National Laboratory  
Post Office Box X  
Oak Ridge, Tennessee 37830



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# Isotope User's Guide

## INTRODUCTION

Radioactive isotopes and enriched stable isotopes were first distributed by Oak Ridge National Laboratory in 1946. However, in the interval since the historic first shipments, practical applications in education, research, industry, and medicine have been developed for most of the stable isotopes but for only relatively few of the more than 1400 radioisotopes known. Oak Ridge National Laboratory now sells only about 50 radioisotopes, and approximately 25 more are available as experimental products. More than 100 other radioisotopes are available from industry. On the other hand, about 250 enriched stable isotopes are available.

Approximately 200 commercially available radioisotopes are listed, with their radiations and production methods included. Definitions of some of the scientific terms usually associated with physics, but also used with radioisotopes, are provided for new users. This guide offers some assistance in choosing an isotope for a specific use, gives some shipping information, and describes special irradiation services. The stable-isotope list includes nearly all of the existing nonradioactive isotopes, since they have all been enriched. Although it is based to a large extent on experience and practice at Oak Ridge National Laboratory, the guide should be helpful wherever isotopes are used.

## ELEMENTARY RADIOISOTOPE PHYSICS

Atoms of different elements are of course different from each other, since they vary from one another in the number of protons and electrons. However, atoms of the same element can also be different from each other. Atoms of a given element all have the same number of electrons and protons but may have different numbers of neutrons in the nucleus. Atoms of an element differing from each other only in the number of neutrons are called *isotopes* of the element. Naturally occurring elements consist of one or more stable isotopes. About 20 elements -- including sodium, aluminum, cobalt, and fluorine -- exist as single stable nuclides; the rest vary from two for several elements -- such as lithium, chlorine, and bromine -- up to ten for tin.

Although most of the natural elements are stable, a few -- such as uranium, thorium, and radium -- are made up entirely of unstable nuclides. Several others -- such as potassium, rubidium, tin, platinum, and neodymium -- consist of a mixture of stable and slightly unstable nuclides. The naturally occurring unstable isotopes are called *natural radioisotopes*; unstable isotopes created artificially (usually from stable isotopes) are called *artificial radioisotopes*.

The breaking up of an unstable atom is accompanied by the phenomenon known as *radioactivity*. In this process the nucleus of an unstable atom changes its makeup, emitting *radiation* during or immediately after this change. The rate of radiation emission for a given isotopic species depends on the total number of

unstable atoms present, and the kind of radiation depends on the particular isotope. As more and more of the original unstable atoms change, the emission rate decreases; the decrease of activity with time is known as *radioactive decay*. The time in which one-half of any starting number of unstable atoms decays is called the *half-life* and is one of the fundamental characteristics used to identify a particular radioactive species. The resulting elements or isotopes are called *decay products* and in some cases are themselves radioactive.

The designation of an isotope follows a certain convention of symbols and numbers. A superscript preceding the element symbol denotes the sum of the numbers of neutrons and protons in the nucleus, that is, the mass (*mass number*) of the isotope. A subscript preceding the element symbol is used to give the *atomic number* of the element, which is the number of protons in the nucleus (and also the number of electrons surrounding the nucleus). Thus,  ${}^{107}_{47}\text{Ag}$  designates the isotope of element 47 (silver) that has 47 protons and 60 neutrons in the nucleus and 47 electrons surrounding the nucleus. Because the symbol Ag and the number 47 both designate the same thing, the element silver, the subscript preceding the symbol is frequently omitted.

The rate of decay is always a constant fraction of the total number of unstable atoms present. In mathematical notation,  $dn/dt = -\lambda n$ , where  $n$  is the number of unstable atoms present at time  $t$ , and  $\lambda$  is the *probability of decay* (or the *decay constant*) per second for the isotope. The half-life – denoted variously  $T$ ,  $T_{1/2}$ , or  $t_{1/2}$  – is related to  $\lambda$  by the equation  $\lambda T = 0.693$ . The probability of decay is higher as the half-life is shorter. Thus, for  ${}^{238}\text{U}$ ,  $T$  is  $4.5 \times 10^9$  years and  $\lambda$  is  $4.88 \times 10^{-18} \text{ sec}^{-1}$ , but for  ${}^{218}\text{At}$ ,  $T$  is 1.3 sec and  $\lambda$  is  $0.53 \text{ sec}^{-1}$ .

### Types of Radiation

There are three principal types of emissions from decaying radioisotopes: alpha, beta, and photon.

**Alpha Radiation.** – An alpha particle is identical to the ordinary helium nucleus. It has two neutrons and two protons. Alpha particles usually move at about one-tenth the speed of light and can be stopped by aluminum foil ~0.002 in. thick. Any nucleus that emits an alpha particle loses two protons and two neutrons; therefore its atomic number decreases by 2 and its mass number decreases by 4. Usually only the very heavy elements emit alpha particles, for example,  ${}^{232}\text{Th} \xrightarrow{\alpha} {}^{228}\text{Ra}$ .

**Beta Radiation.** – Beta particles are electrons and usually move at very nearly the speed of light; they can have either a positive or a negative charge and are called *positrons* and *negatrons* respectively. An atom that emits beta particles can do one of two things. If the beta particle emitted is a positron, then a proton in the nucleus becomes a neutron. The atomic number decreases by 1, but the mass number remains unchanged. If the beta particle emitted is a negatron, a neutron in the nucleus becomes a proton. The atomic number increases by 1, but again the mass number is unchanged. Examples are  ${}^{120}\text{Sb} \xrightarrow{\beta^+} {}^{120}\text{Sn}$  and  ${}^{121}\text{Sn} \xrightarrow{\beta^-} {}^{121}\text{Sb}$ .

**Photon Radiation.** – Gamma rays are photons of electromagnetic energy that originate in the nucleus. When a nucleus emits a gamma ray, the only change is to a less energetic form of the same isotope; for example,  ${}^{125m}\text{Te} \xrightarrow{\gamma} {}^{125}\text{Te}$ . Photons other than gamma rays, such as x rays, come from internal conversion, electron capture, and the bremsstrahlung process (see *Sources of photon radiation*, below).

### Energies of Radiation

The energy of the particles (alpha and beta radiation) is the kinetic energy for moving particles,  $E = mv^2/2$ , where  $m$  = mass and  $v$  = velocity. Gamma radiation energy is in the form of radiant energy, that is, photons. This energy is usually expressed in millions of electron volts (MeV);  $1 \text{ eV} = 1.602 \times 10^{-12} \text{ erg}$ .

### Dose

*Radiation dose* is a vague term borrowed from medical and radiological terminology. To avoid vagueness, one should speak of *exposure dose* and *absorbed dose*. Exposure dose is a quantity of radiation defined in terms of its effect on dry air under standard conditions; absorbed dose is the amount of energy transmitted by radiation to any medium. Their units are the *roentgen* and the *rad* respectively. The roentgen (R) measures energy transmitted to the air along the path of radiation, mainly in the form of ionization, and cannot be used to describe particle emission. One roentgen equals 83 ergs per gram of dry air. The rad is the quantity of ionizing radiation of any kind which when absorbed by a substance causes an energy gain of 100 ergs per gram of that substance. For most purposes the roentgen and the rad are essentially the same. Since the rad does not specify an absorbing medium, the quantity of radiation it defines is not exact; but since it does define a quantity of absorbed radiation, it can be used to talk about the effects of any type of radiation.

*Exposure dose rate* and *absorbed dose rate* are both simply dose per unit time. The gamma output of a radioactive source is the exposure dose rate it produces at a given distance. Commonly used expressions are roentgens per hour at 1 m (rhm) and roentgens per minute at 1 m (rmm). The relation between exposure dose rate and absorbed dose rate is

$$R = \frac{D(\text{medium})}{0.877} \times \frac{\mu(\text{air})}{\mu(\text{medium})}$$

where  $R$  is the exposure dose rate in roentgens per hour,  $D$  is the absorbed dose rate in rads per hour, and  $\mu$  is the linear energy absorption coefficient (a measure of the amount of energy a material will absorb when exposed to a given quantity of radiation).

### Shielding

Alpha and beta particles do not usually present serious shielding problems. The former can be stopped by aluminum foil about 0.002 in. thick, and the latter can be stopped by about 1 in. of aluminum. Beta particles do sometimes cause x rays to be emitted from materials of high atomic number, as mentioned previously. This bremsstrahlung (German for "braking radiation") is caused by the interaction of the beta particle with the strong electric field surrounding the nucleus. The same shielding laws apply to bremsstrahlung as apply to gamma radiation. Gamma rays and neutrons do raise serious shielding problems.

**Gamma Shielding.** — Without shielding and neglecting air absorption, the dose rate from a small source varies inversely as the square of the distance from the source. According to this *inverse-square law*, if 1 Ci (curie) of  $^{60}\text{Co}$  produces 4 rads/h at a given distance, it will produce only 1 rad/h at twice that distance.

Gamma radiation is attenuated roughly in proportion to the density (and to the atomic number) of the shielding material, usually lead or concrete. Tungsten and other materials are better but more expensive. Attenuation obeys the law  $I_x = I_0 e^{-\mu x}$ , where  $I_0$  is the exposure dose rate at a given point,  $I_x$  is the exposure dose rate at the same point with material of thickness  $x$  between source and point, and  $\mu$  is the linear energy absorption coefficient of the material. The *half-thickness* is the thickness of shielding required to reduce the exposure dose rate by half; the half-thickness is related to the linear energy absorption coefficient by the rule  $x_{1/2} = 0.693/\mu$ . The absorption coefficient is usually read from available graphs.

A calculator designed to give rapid and direct solutions to handling and shielding problems associated with the more commonly used gamma emitters is available from the United Kingdom Atomic Energy

Authority.\* The device, which resembles a circular slide rule, has scales for  $^{137}\text{Cs}$ ,  $^{60}\text{Co}$ ,  $^{198}\text{Au}$ ,  $^{131}\text{I}$ ,  $^{192}\text{Ir}$ ,  $^{226}\text{Ra}$ , and  $^{24}\text{Na}$ . The activity scale extends to 1000 Ci, and the shield thickness scale goes to 30 cm of lead.

**Neutron Shielding.** — Although neutrons are not emitted directly by any of the more familiar radioisotopes, they are one of the most important types of radiation. They are released in very large numbers in fission in reactors, but other neutron sources are available. Neutrons are more penetrating than any of the other particle radiations, since they are uncharged and hence unaffected by positive or negative charges in the material through which they pass. Neutron attenuation is based on the neutron absorption characteristics of certain materials rather than on density. Usually a neutron source is surrounded by a moderator, which slows fast neutrons down to thermal neutrons by a series of “billiard-ball” collisions, and a shield made of a material that absorbs thermal neutrons. A good moderator is heavy water;  $\text{D}_2\text{O}$  is used in reactors sometimes for just this reason, since regular, or light, water would absorb fast neutrons. Most moderators are compounds of hydrogen.

*Isotopic neutron sources* are usually made by mixing an alpha emitter with beryllium (although  $^{252}\text{Cf}$  undergoes spontaneous fission to provide an intense source of neutrons). The alpha particles are captured by the beryllium nuclei, which then emit neutrons. Alpha-neutron sources also sometimes emit gamma rays; these are emitted by the alpha source, by the nuclei left in an excited state by the alpha-neutron reaction, or by impurities in the alpha emitter. Sufficiently energetic gammas can induce neutron emission from some nuclei. The emitted neutron has the energy  $E_n = E_\gamma - T$ , where the threshold energy  $T$  is the minimum gamma energy needed to produce the reaction. Except for beryllium ( $T = 1.67$  MeV) and deuterium ( $T = 2.23$  MeV),  $T$  exceeds 6 MeV for all possible target materials. No gamma ray from any known radioisotope has such energy; so all radioisotope gamma-neutron sources use either beryllium or deuterium as targets. This fact is important because it explains the safety of the AEC's low-dose food irradiation program; activities induced by gamma emission from  $^{60}\text{Co}$ ,  $^{137}\text{Cs}$ , and most machine irradiators are negligible.

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## DEFINITIONS OF COMMON TERMS USED IN ISOTOPE AND RADIATION TECHNOLOGY

*Annihilation gamma rays* are photons that come from collisions between positive and negative electrons, and two photons (0.51 MeV each) result from the disappearance (annihilation) of the two kinds of electrons.

*Auger (oh-zhay) electrons* are electrons emitted or knocked out of orbit by energy released by electron-shell adjustment.

*Bergonie-Tribondeau law* describes the effect of radiation on cells of living organisms. It states that the sensitivity of cells to radiation is in direct proportion to their reproductive activity and inversely proportional to their degree of specialization.

*Bremsstrahlung* -- see "Sources of photon radiation."

*Carrier-free* denotes a radioisotope of an element in which all the atoms of that element present are radioactive. However, this ideal is usually only approached. The term is sometimes used to mean *no added carrier*; that is, no significant quantity of the element in question is added to facilitate chemical processing.

*Cerenkov radiation* is visible light given off by charged particles moving through some dense medium at a speed greater than the speed of light in that medium. It is usually seen as a blue glow around the core of a reactor or some other intense radiation source.

*Counting geometry* refers to the geometrical arrangement of the sample to be counted, the window used, and the detector itself.

*Cross section* is a measure of the probability of interaction between a target nucleus and a bombarding particle, usually a neutron or a proton. The *neutron activation cross section* is the probability that a neutron will hit a target nucleus and produce a specified radioisotope; *capture cross section* is the probability that a neutron will be captured by a target atom. Both are mathematically expressed as a small area surrounding the nucleus; the unit of expression is the *barn*, which is  $10^{-24}$  cm<sup>2</sup>. Values ordinarily listed in cross-section tables are the isotopic cross sections; that is, they are applicable only to the particular isotope under consideration.

*Curie* is the quantity of a radioisotope required to supply  $3.7 \times 10^{10}$  nuclear disintegrations per second; it corresponds approximately to the number of disintegrations from 1 g of radium. In the case of a mixture of radioisotopes for which an absolute measurement cannot be made, the apparent disintegration rate may be compared to a known standard and the activity calculated. Sometimes a curie is taken as  $3.7 \times 10^{10}$  beta counts per second, estimated by standard counting procedures and corrected only for counting geometry. A *millicurie* (mCi) is  $1 \times 10^{-3}$  Ci (1/1000 of a curie), and a *microcurie* is  $1 \times 10^{-6}$  Ci (1/1,000,000 of a curie).

*Decay series* are chains of decay that start with some of the very heavy radioactive elements. There are four series in all, three of which occur in nature:  $4n$  is the thorium decay chain that goes from  $^{232}\text{Th}$  to  $^{208}\text{Pb}$ ;  $4n + 1$  is the neptunium decay chain that goes from  $^{241}\text{Pu}$  to  $^{209}\text{Bi}$ ;  $4n + 2$  is the uranium decay chain that goes from  $^{238}\text{U}$  to  $^{206}\text{Pb}$ ;  $4n + 3$  is the actinium decay chain that goes from  $^{235}\text{U}$  to  $^{207}\text{Pb}$ . The neptunium decay chain does not occur in nature, although it must have at one time. The terms  $4n$ ,  $4n + 1$ ,  $4n + 2$ , and  $4n + 3$  mean that the mass number of each nuclide in the chain is divisible by 4, with the remainder 0, 1, 2, or 3. The decay chains are illustrated in Figs. 1 to 4.

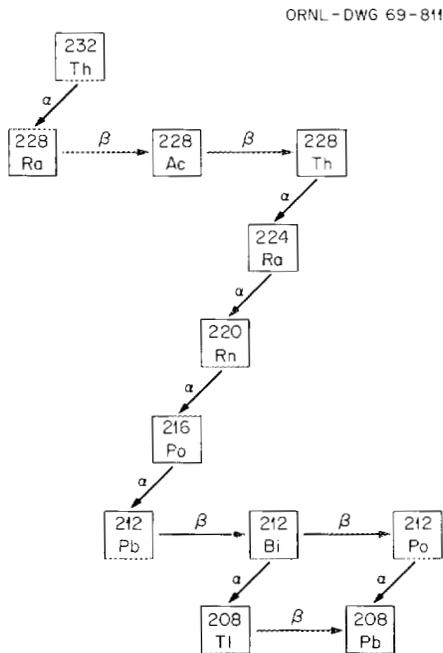
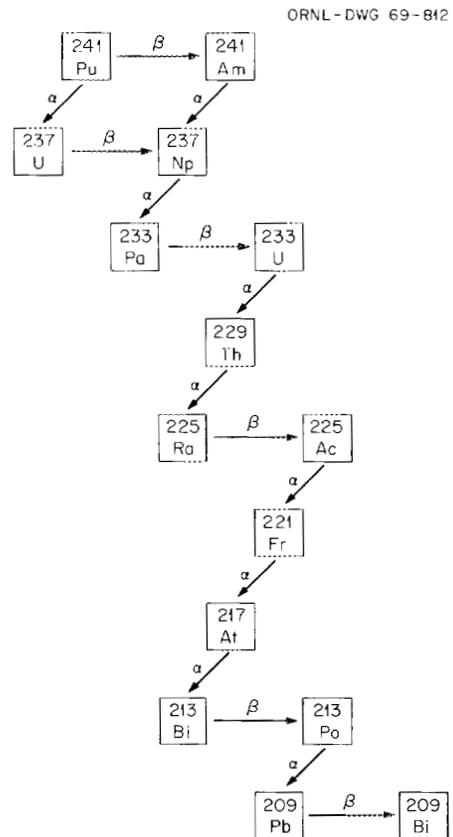
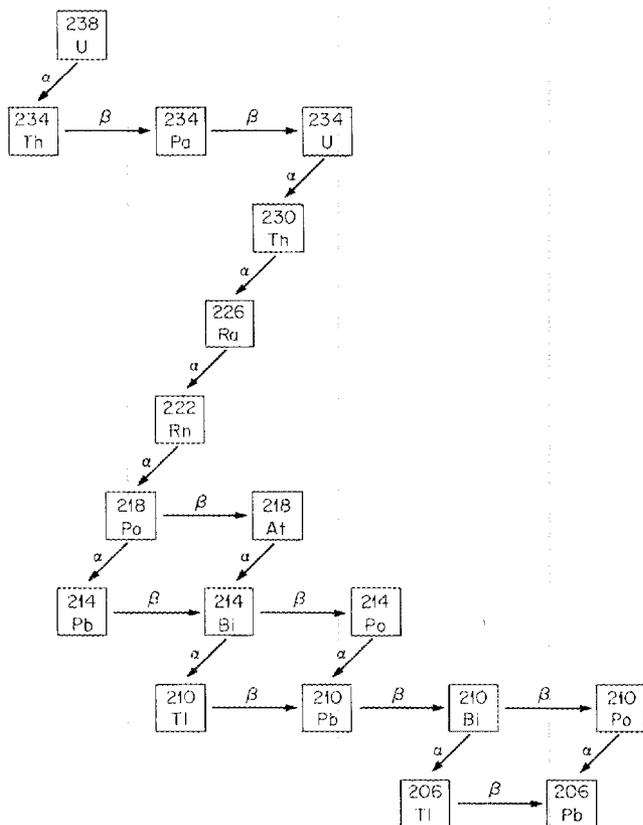
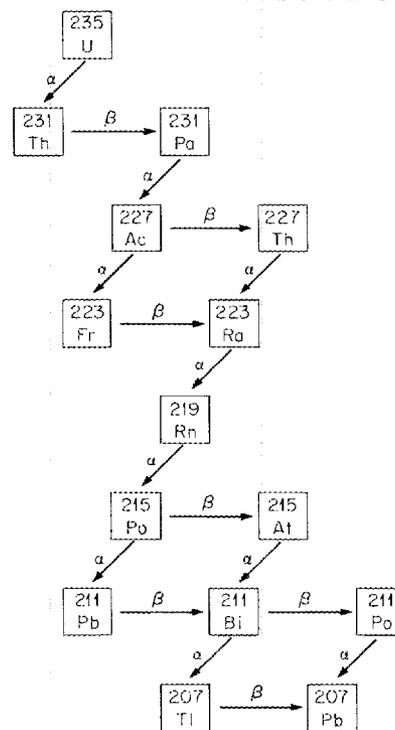


Fig. 1. The  $4n$  Thorium Natural Decay Series.

Fig. 2. The  $4n + 1$  Neptunium Decay Series.



Fig. 3. The  $4n + 2$  Uranium Natural Decay Series.Fig. 4. The  $4n + 3$  Actinium Natural Decay Series.

*Electron capture* occurs when an unstable nucleus captures one of its own orbital electrons, with the result that a proton disappears and a neutron appears. The atomic number decreases by one, but the mass number is unchanged. The resulting shifts in the external electrons to balance their shell structures cause x rays to be emitted. Capture from a particular electron shell is indicated by use of the letter designating that shell; for example, *K*-capture is capture of an electron from the *K* shell.

*Internal conversion* is the emission of an orbital electron from the atom, which results from the interaction between the electron and a gamma ray emitted by the nucleus. Afterward, adjustments in the electrons to fill the vacancy result in emission of characteristic x radiation or Auger electrons.

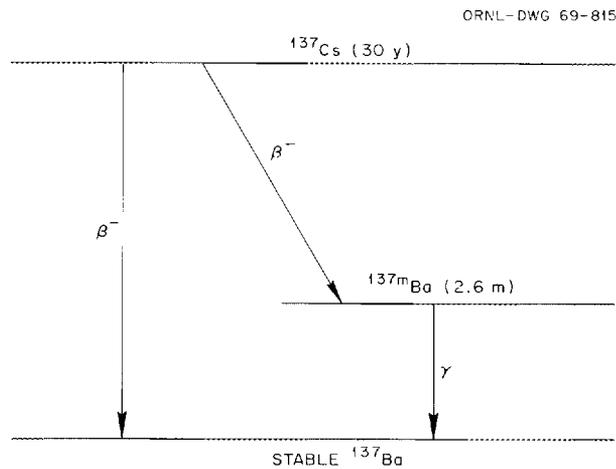
*In vivo* and *in vitro* mean, respectively, in the living body and out of the living body.

*Ions* are atoms with more or less electrons than the atoms have in the elemental state. When an electron is removed from an atom, the atom loses a negative charge and thus becomes positively charged by virtue of one excess proton in the nucleus. If a free electron attaches itself to an atom, the atom becomes negatively charged by virtue of one excess electron in its shell structure. Any charged atom is an ion.

*Mössbauer effect* is recoilless nuclear resonance absorption or scattering. It is used to measure changes in the energy of gamma emissions and is very sensitive. Atoms with excited states having a half-life  $T > 10^{-11}$  sec and emitting low-energy gamma rays ( $< 200$  keV) are likely to show the Mössbauer effect.

*Neutron flux* is the amount of flow of neutrons through a given area in a given time and is usually expressed as neutrons  $\text{cm}^{-2} \text{sec}^{-1}$ . Neutrons emitted by the nuclear reactions in the core of a reactor are called *fast neutrons*. They move at high speeds and have energies of the order of a million electron volts. Collisions, particularly with moderators (such as carbon and hydrogen), slow down these fast neutrons until they are in thermal equilibrium with the surrounding medium. *Thermal neutrons* move at speeds of about 2200 m/sec and have energies  $< 1$  eV.

*Nuclear isomerism* occurs when atoms of the same isotope are formed in either of two different energy states and decay at different rates. In some cases two *isomers* decay independently to some third ground state. In other cases the upper energy level (the metastable state) decays to the lower energy level; this is known as *isomeric transition* and is accompanied by gamma emission. In the schematic shown,  $^{137\text{m}}\text{Ba}$  is an isomer of  $^{137}\text{Ba}$ :



*Percentage yield* is the number of designated particles or photons released per 100 nuclear disintegrations.

*Purity* usually means radiochemical purity, that is, the relative freedom from other radioelements contributing extraneous radioactivities. Activity from decay products, sometimes called *daughters*, and activity from other radioisotopes of the same element are not considered impurities. For example, the presence of  $^{124}\text{Sb}$  in  $^{122}\text{Sb}$  would not be considered in calculating the purity of  $^{122}\text{Sb}$ . The approximate amount of other isotopes of the same element present is usually included in any descriptive information shipped with an isotope.

*Sources of photon radiation:* Gamma rays come only from a nucleus; x rays come from electron shells. *Bremsstrahlung* – that is, a continuous spectrum of x rays – is the electromagnetic radiation produced by the slowing down of electrons as they pass through matter. Positron–negatron collisions produce *annihilation gamma rays*.

*Specific activity*, in the true sense, is the activity of a radioisotope per unit weight of that isotope. However, it has also come to mean the activity of a radioisotope per unit weight of element present. As a result of this ambiguity, the terms *radioisotope abundance* and *activity concentration* have been suggested as substitutes, since they are more general and can be stated in atom percent and weight percent, as well as in curies per gram. Specific activity is usually expressed as millicuries or curies per gram.

## SELECTION OF A RADIOISOTOPE

### How to Choose a Radioisotope

The great diversity of radioactive materials now available sometimes makes choosing an isotope for a specific purpose difficult. The right choice requires careful consideration of such factors as personnel safety, characteristics of the radioisotope, possible chemical reactions, economics, and availability. Isotopes for medical use -- therapy or diagnosis -- are chosen quite differently from isotopes used as tracers in ecological studies, and these, in turn, quite differently from isotopes used as radiation sources in gages for industry. In any work using radioisotopes, the type of emitter -- alpha, beta, or photon -- must first be decided. For industrial gages, beta emitters are usually chosen whenever feasible, since they require less shielding and can be detected with greater efficiency than gamma rays. In those cases where the radiation must be detected through appreciable thicknesses of material or from a considerable distance -- as in detecting underground leaks -- a gamma emitter is the only choice possible. Gamma emitters are used in medical diagnosis and therapy because of their greater penetrability, which means smaller amounts can be used in the body. Alpha emitters are not used as often as beta or gamma emitters because of their low penetrating power, but they do find considerable use in ionization of gases and in initiation of secondary reactions.

The actual conditions of a proposed experiment, of course, dictate the final choice of radioisotope. Once these conditions are established, however, the choice is still not a simple one. Suppose a gamma emitter is to be chosen for an experiment that will require appreciable penetrating power and last 48 h. For safety, the residual activity should be minimized. Since activity diminishes by the rule  $A/A_0 = (1/2)^n$ , where  $A$  is the present activity,  $A_0$  the initial activity, and  $n$  the number of half-lives, the required high-energy gamma emitter should have a half-life of about 10 to 15 h. Tables 4 and 5 show that  $^{24}\text{Na}$  with a half-life of 15 h (Table 5) and two hard gamma emissions (Table 4) is probably the best choice, with  $^{42}\text{K}$  another possibility. In this example, half-life was the deciding factor; another experiment might require that this consideration take second place to a need for a high penetrating energy.

In most practical applications of radioisotopes, the emitted radiation is not measured directly by the radiation monitoring apparatus; rather, the apparatus measures only the radiation incident upon it -- an attenuated portion of the radiation emitted by the radioisotope. Therefore, the user of radioisotopes must be aware of the measurement problems posed by attenuation of radiation. The equation for attenuation is given on p. 3 (under "Gamma Shielding").

Precautions necessary to protect personnel working with gamma sources depend upon the energy of the radiation emitted by the source. The absorbed dose rate can be calculated from the disintegration rate if the relation between dose rate and photon flux is also known. This relation is approximately linear between 70 keV and 2 MeV:  $1 \text{ R} = 1.9 \times 10^9/E$  (photons/cm<sup>2</sup>), which is

Table 1. Dose Rates for Some Radioisotopes

Radioisotope	Dose Rate (rhm <sup>a</sup> /Ci)
<sup>24</sup> Na	1.93
<sup>51</sup> Cr	0.018
<sup>59</sup> Fe	0.65
<sup>60</sup> Co	1.35
<sup>131</sup> I	0.29
<sup>137</sup> Cs	0.32
<sup>140</sup> La	1.2
<sup>170</sup> Tm	0.004
<sup>182</sup> Ta	0.6
<sup>192</sup> Ir	0.5
<sup>198</sup> Au	0.23
Radium (including daughter products)	0.825

<sup>a</sup>rhm means roentgens per hour at a distance of 1 m; this does not include beta particles.

accurate to  $\pm 15\%$ . Personnel-absorbed dose rate\* should not exceed 100 mR/week and, of course, should be less whenever possible. The equation for radiation emitted by an unshielded source is

$$d = 1.06 \times 10^{13} (Q/l^2) \sum (N_E/P_E) ,$$

where  $Q$  is quantity of the isotope in curies,  $l$  is distance from the source in cm,  $N_E$  is the number of photons per disintegration, and  $P_E$  is photons  $\text{cm}^{-2} \text{R}^{-1}$  for energy  $E$  (based on the roentgen rule above). The emitted doses for some common radioisotopes are given in Table 1.

Another factor to be considered, especially in material tracing and in medical studies, is the possibility of an unexpected and undesirable chemical reaction between the substance containing the radioisotope and the system being studied. Radioactive arsenic and similar materials are not likely to be used as tracers in the human body in concentrations approaching tolerance limits. Neither is radioactive chlorine to be used to trace fluids through a pipeline made of unannealed stainless steel. "Boneseekers," such as calcium and strontium, may be undesirable for medical injections.

Cost is another factor encouraging use of a minimum amount of radioisotope. Isotopes are research materials and are not inexpensive. A quantity that will give satisfactory detection and measurement is required, and usually this means the quantity that will produce a counting rate double that of background. For ease of working, and to allow for losses, slightly higher levels are preferable.

#### Tables of Beta and Gamma Emitters

Few radioisotopes emit only one kind of radiation. However, some emit so little of any other kind that they can be considered as emitters of one kind only. In the three tables that follow (Tables 2-4) are listed "pure" beta emitters, "pure" gamma emitters, and hard gamma emitters. (The "pure," remember, does not necessarily mean that only beta radiation or that only gamma radiation is emitted; it simply means that, for most practical purposes, the other radiations can be ignored.)

\*Radiation Safety and Control Training Manual, Oak Ridge National Laboratory, 1961.

For the table of hard gamma emitters, those radioisotopes were chosen that emit gamma photons of energy greater than 1 MeV more than 5% of the time; likewise, for these radioisotopes, no claim is made that they emit only one sort of radiation.

Table 2. Pure Beta Emitters

Isotope	Maximum Energy (MeV)	Isotope	Maximum Energy (MeV)	Isotope	Maximum Energy (MeV)
$^{90}\text{Y}$	2.28	$^{36}\text{Cl}$	0.71	$^{33}\text{P}$	0.25
$^{97}\text{Zr}^a$	1.90	$^{127}\text{Te}$	0.70	$^{147}\text{Pm}$	0.22
$^{32}\text{P}$	1.71	$^{113m}\text{Cd}$	0.58	$^{66}\text{Ni}^d$	0.20
$^{91}\text{Y}$	1.54	$^{39}\text{Ar}$	0.56	$^{35}\text{S}$	0.167
$^{31}\text{Si}$	1.48	$^{10}\text{Be}$	0.55	$^{14}\text{C}$	0.156
$^{89}\text{Sr}$	1.46	$^{90}\text{Sr}^a$	0.54	$^{151}\text{Sm}$	0.076
$^{210}\text{Bi}^a$	1.17	$^{185}\text{W}$	0.43	$^{63}\text{Ni}$	0.067
$^{109}\text{Pd}^a$	1.02	$^{121}\text{Sn}$	0.38	$^{228}\text{Ra}^a$	0.05
$^{143}\text{Pr}$	0.93	$^{188}\text{W}^a$	0.35	$^{227}\text{Ac}^a$	0.045
$^{69}\text{Zn}$	0.90	$^{99}\text{Tc}$	0.29	$^{106}\text{Ru}^a$	0.039
$^{204}\text{Tl}$	0.76	$^{45}\text{Ca}$	0.26	$^3\text{H}$	0.018

<sup>a</sup>Decays to daughter product(s) having other radiations that must be considered.

Table 3. Pure Gamma Emitters<sup>a</sup>

Isotope	Maximum Energy (MeV) <sup>b</sup>	Isotope	Maximum Energy (MeV) <sup>b</sup>	Isotope	Maximum Energy (MeV) <sup>b</sup>
$^{88}\text{Y}$	1.84	$^{67}\text{Ga}$	0.39(0.093)	$^{123}\text{I}$	0.16
$^{207}\text{Bi}$	1.77(0.57)	$^{87m}\text{Sr}$	0.39	$^{183}\text{Re}$	0.16
$^{206}\text{Bi}$	1.72(0.80)	$^{113m}\text{In}$	0.39	$^{123m}\text{Te}$	0.16
$^{185}\text{Os}$	0.88(0.65)	$^{133}\text{Ba}$	0.38(0.36)	$^{99m}\text{Tc}$	0.14
$^{54}\text{Mn}$	0.835	$^{175}\text{Hf}$	0.34	$^{57}\text{Co}$	0.136(0.122)
$^{131}\text{Ba}$	0.60(0.50)	$^{105}\text{Ag}$	0.34	$^{197m}\text{Hg}$	0.134
$^{77}\text{Br}$	0.58(0.24)	$^{97}\text{Ru}$	0.32(0.22)	$^{153}\text{Gd}$	0.10
$^{121}\text{Te}$	0.57	$^{51}\text{Cr}$	0.32	$^{44}\text{Ti}$	0.078
$^{83}\text{Rb}$	0.55	$^{173}\text{Lu}$	0.27	$^{197}\text{Hg}$	0.077
$^{85}\text{Sr}$	0.51	$^{111}\text{In}$	0.25	$^{125}\text{I}$	0.035
$^7\text{Be}$	0.48	$^{121m}\text{Te}$	0.21	$^{125m}\text{Te}$	0.035
$^{87}\text{Y}$	0.48	$^{169}\text{Yb}$	0.20(0.063)	$^{119m}\text{Sn}$	0.024
$^{75}\text{Se}$	0.40(0.26-0.28)	$^{139}\text{Ce}$	0.17		

<sup>a</sup>Most pure gamma emitters also emit x rays. Sometimes these x rays are of greater intensity than the gammas, and this must be considered carefully when choosing a gamma emitter.

<sup>b</sup>Where the maximum energy is not the principal (most abundant) energy, the principal energy is listed in parentheses.

Table 4. Hard Gamma Emitters<sup>a</sup>

Isotope	Maximum Energy (MeV)	Isotope	Maximum Energy (MeV)	Isotope	Maximum Energy (MeV)
<sup>56</sup> Co	3.25	<sup>26</sup> Al	1.81	<sup>28</sup> Mg	1.35
	2.6	<sup>28</sup> Al	1.78	<sup>60</sup> Co	1.33
	2.04	<sup>207</sup> Bi	1.77		1.17
	1.77		1.06	<sup>48</sup> V	1.31
	1.24	<sup>206</sup> Bi	1.72	<sup>47</sup> Ca	1.30
<sup>24</sup> Na	1.04	<sup>124</sup> I	1.69	<sup>59</sup> Fe	1.29
	2.75	<sup>140</sup> La	1.60		1.10
<sup>66</sup> Ga	1.37	<sup>42</sup> K	1.52	<sup>154</sup> Eu	1.28
	2.75	<sup>110</sup> Ag	1.50		1.00–1.01
<sup>72</sup> Ga	1.04		1.38	<sup>22</sup> Na	1.27
	2.5	<sup>82</sup> Br	1.47	<sup>182</sup> Ta	1.22–1.23
<sup>38</sup> Cl	2.20		1.32		1.19
	2.17		1.04		1.12
<sup>56</sup> Mn	1.64	<sup>65</sup> Ni	1.48	<sup>76</sup> As	1.22
	2.11		1.11	<sup>44</sup> Sc	1.16
<sup>116m</sup> In	1.81	<sup>40</sup> K	1.46	<sup>130</sup> I	1.15
	2.1	<sup>52</sup> Mn	1.43	<sup>46</sup> Sc	1.12
	1.29	<sup>152</sup> Eu	1.41	<sup>65</sup> Zn	1.12
<sup>124</sup> Sb	1.09		1.09–1.11	<sup>86</sup> Rb	1.08
	2.09			<sup>66</sup> Cu	1.04
	1.69				
<sup>88</sup> Y	1.30				
	1.84				

<sup>a</sup>Listed here are those gamma emitters that emit gamma photons having an energy greater than 1 MeV and occurring in greater than 5% abundance. Where a radionuclide emits more than one gamma with energy greater than 1 MeV, all gammas over 1 MeV are listed.

## Available Radioisotopes Listed According to Half-Life

To facilitate the choice of a radioisotope for a specific application, the available radioisotopes are listed in Table 5 in order of increasing half-life.

Table 5. Available Radioisotopes Listed According to Half-Life

Half-Life <sup>a</sup>	Radioisotopes	Radiation	Half-Life <sup>a</sup>	Radioisotopes	Radiation
37.3 m	<sup>38</sup> Cl	$\beta^-$ , $\gamma$	28 h	<sup>151</sup> Pm	$\beta^-$ , $\gamma$ , $e^-$
54 m	<sup>116m1</sup> In	$\beta^-$ , $\gamma$	32 h	<sup>193</sup> Os	$\beta^-$ , $\gamma$ , $e^-$
57 m	<sup>103m</sup> Rh	IT, $e^-$	33 h	<sup>143</sup> Ce	$\beta^-$ , $\gamma$ , $e^-$
1.8 h	<sup>149</sup> Nd	$\beta^-$ , $\gamma$ , $e^-$	35 h	<sup>79</sup> Kr	$\beta^+$ , EC, $\gamma$
1.83 h	<sup>18</sup> F	$\beta^+$ , EC	35.4 h	<sup>82</sup> Br	$\beta^-$ , $\gamma$
2.3 h	<sup>132</sup> I	$\beta^-$ , $\gamma$	36 h	<sup>105</sup> Rh	$\beta^-$ , $\gamma$
2.35 h	<sup>165</sup> Dy	$\beta^-$ , $\gamma$	38.7 h	<sup>77</sup> As	$\beta^-$ , $\gamma$
2.56 h	<sup>65</sup> Ni	$\beta^-$ , $\gamma$	40.2 h	<sup>140</sup> La	$\beta^-$ , $\gamma$
2.58 h	<sup>56</sup> Mn	$\beta^-$ , $\gamma$	46.8 h	<sup>153</sup> Sm	$\beta^-$ , $\gamma$
2.62 h	<sup>31</sup> Si	$\beta^-$	53 h	<sup>149</sup> Pm	$\beta^-$ , $\gamma$
2.8 h	<sup>87m</sup> Sr	IT, $e^-$	55 h, 5 m	<sup>66</sup> Ni- <sup>66</sup> Cu	$\beta^-$ , $\gamma$
3.9 h	<sup>44</sup> Sc	$\beta^+$ , EC, $\gamma$	55 h, 4.5 h	<sup>115</sup> Cd- <sup>115m</sup> In	$\beta^-$ , $\gamma$ , IT, $e^-$
4.4 h	<sup>85m</sup> Kr	$\beta^-$ , IT, $\gamma$ , $e^-$	56 h	<sup>77</sup> Br	EC, $\gamma$ , $e^-$
6.7 h	<sup>234</sup> Pa	$\beta^-$ , $\gamma$ , $e^-$	61.7 h	<sup>67</sup> Cu	$\beta^-$ , $\gamma$
7.5 h	<sup>171</sup> Er	$\beta^-$ , $\gamma$	64.0 h	<sup>90</sup> Y	$\beta^-$
8.3 h	<sup>52</sup> Fe	$\beta^+$ , EC, $\gamma$	64 h	<sup>197</sup> Hg	EC, $\gamma$ , $e^-$
9.3 h	<sup>152m1</sup> Eu	$\beta^-$ , EC, $\gamma$ , $e^-$	2.70 d	<sup>198</sup> Au	$\beta^-$ , $\gamma$
9.5 h	<sup>66</sup> Ga	$\beta^+$ , EC, $\gamma$	2.7 d	<sup>122</sup> Sb	$\beta^-$ , EC, $\gamma$
11.3 h	<sup>77</sup> Ge	$\beta^-$ , $\gamma$	66.3 h, 6.02 h	<sup>99</sup> Mo- <sup>99m</sup> Tc	$\beta^-$ , IT, $\gamma$
12.3 h	<sup>130</sup> I	$\beta^-$ , $\gamma$	67.4 h	<sup>111</sup> In	EC, $\gamma$ , $e^-$
12.4 h	<sup>42</sup> K	$\beta^-$ , $\gamma$	69.6 h	<sup>97</sup> Ru	EC, $\gamma$ , $e^-$
12.7 h	<sup>64</sup> Cu	$\beta^-$ , $\beta^+$ , EC, $\gamma$	3.15 d	<sup>199</sup> Au	$\beta^-$ , $\gamma$ , $e^-$
12.8 h	<sup>150</sup> Eu	$\beta^-$ , EC, $\gamma$ , $e^-$	78 h	<sup>132</sup> Te	$\beta^-$ , $\gamma$ , $e^-$
13 h	<sup>123</sup> I	EC, $\gamma$ , $e^-$	78 h	<sup>67</sup> Ga	EC, $\gamma$ , $e^-$
13 h	<sup>191m</sup> Os	IT, $e^-$	80 h	<sup>87</sup> Y	EC, $\gamma$
13.6 h, 40 s	<sup>109</sup> Pd- <sup>109m</sup> Ag	$\beta^-$ , IT, $e^-$	3.4 d	<sup>47</sup> Sc	$\beta^-$ , $\gamma$
14 h, 55 m	<sup>69m-69</sup> Zn	IT, $\beta^-$ , $e^-$	87.4 h	<sup>224</sup> Ra	$\alpha$ , $\gamma$
14.1 h	<sup>72</sup> Ga	$\beta^-$ , $\gamma$	90 h	<sup>186</sup> Re	$\beta^-$ , $\gamma$ , $e^-$
15.0 h	<sup>24</sup> Na	$\beta^-$ , $\gamma$	3.82 d	<sup>222</sup> Rn	$\alpha$
17 h	<sup>188</sup> Re	$\beta^-$ , $\gamma$ , $e^-$	4.2 d	<sup>175</sup> Yb	$\beta^-$ , $\gamma$ , $e^-$
17 h, 1.0 m	<sup>97m-97</sup> Zr	$\beta^-$ , $\gamma$	4.2 d	<sup>124</sup> I	EC, $\beta^+$ , $\gamma$
18 h	<sup>159</sup> Gd	$\beta^-$ , $\gamma$ , $e^-$	4.3 d	<sup>193m</sup> Pt	IT, $e^-$
19.2 h	<sup>142</sup> Pr	$\beta^-$ , $\gamma$	4.53 d, 3.4 d	<sup>47</sup> Ca- <sup>47</sup> Sc	$\beta^-$ , $\gamma$
19.4 h	<sup>194</sup> Ir	$\beta^-$ , $\gamma$	5.0 d	<sup>210</sup> Bi	$\beta^-$
20 h	<sup>197</sup> Pt	$\beta^-$ , $\gamma$ , $e^-$	5.3 d	<sup>133</sup> Xe	$\beta^-$ , $\gamma$
20.9 h	<sup>133</sup> I	$\beta^-$ , $\gamma$	5.7 d	<sup>52</sup> Mn	EC, $\beta^+$ , $\gamma$
21.1 h, 2.25 m	<sup>28</sup> Mg- <sup>28</sup> Al	$\beta^-$ , $\gamma$	6.24 d	<sup>206</sup> Bi	EC, $\gamma$ , $e^-$
22 h	<sup>43</sup> K	$\beta^-$ , $\gamma$	6.5 d	<sup>132</sup> Cs	EC, $\beta^-$ , $\gamma$
24 h, 64 h	<sup>197m-197</sup> Hg	IT, EC, $\gamma$ , $e^-$	6.7 d	<sup>177</sup> Lu	$\beta^-$ , $\gamma$ , $e^-$
24 h	<sup>187</sup> W	$\beta^-$ , $e^-$ , $\gamma$	6.9 d	<sup>161</sup> Tb	$\beta^-$ , $\gamma$ , $e^-$
26.4 h	<sup>76</sup> As	$\beta^-$ , $\gamma$	7.5 d	<sup>111</sup> Ag	$\beta^-$ , $\gamma$
27.0 h	<sup>166</sup> Ho	$\beta^-$ , $\gamma$ , $e^-$	8 d	<sup>129m</sup> Xe	IT, $e^-$
27 h	<sup>121</sup> Sn	$\beta^-$	8.06 d	<sup>131</sup> I	$\beta^-$ , $\gamma$ , $e^-$

<sup>a</sup>s, second; m, minute; h, hour; d, day; y, year.

Table 5 (continued)

Half-Life <sup>a</sup>	Radioisotopes	Radiation	Half-Life <sup>a</sup>	Radioisotopes	Radiation
9.3 d	<sup>169</sup> Er	$\beta^-$ , $\gamma$ , $e^-$	80 d	<sup>73</sup> As	EC, $\gamma$ , $e^-$
9.7 d	<sup>131</sup> Cs	EC	83 d	<sup>83</sup> Rb	EC, $\gamma$ , $e^-$
11.1 d	<sup>147</sup> Nd	$\beta^-$ , $\gamma$ , $e^-$	84 d	<sup>46</sup> Sc	$\beta^-$ , $\gamma$
11.4 d	<sup>71</sup> Ge	EC	88 d	<sup>35</sup> S	$\beta^-$
12 d, 9.7 d	<sup>131</sup> Ba- <sup>131</sup> Cs	EC, $\gamma$ , $e^-$	94 d	<sup>185</sup> Os	EC, $\gamma$ , $e^-$
12 d	<sup>131m</sup> Xe	IT, $e^-$	107 d	<sup>88</sup> Y	EC, $\gamma$
12.8 d, 40.2 h	<sup>140</sup> Ba- <sup>140</sup> La	$\beta^-$ , $\gamma$	109 d, 9.3 h	<sup>127m-127</sup> Te	IT, $\beta^-$ , $e^-$
13 d	<sup>126</sup> I	EC, $\beta^-$ , $\gamma$	115 d	<sup>182</sup> Ta	$\beta^-$ , $\gamma$ , $e^-$
13.6 d	<sup>143</sup> Pr	$\beta^-$	115 d, 1.7 h	<sup>113</sup> Sn- <sup>113m</sup> In	EC, IT, $\gamma$ , $e^-$
14.3 d	<sup>32</sup> P	$\beta^-$	120 d	<sup>123m</sup> Te	IT, $\gamma$ , $e^-$
15 d	<sup>191</sup> Os	$\beta^-$ , $\gamma$ , $e^-$	120 d	<sup>75</sup> Se	EC, $\gamma$ , $e^-$
16.1 d	<sup>48</sup> V	$\beta^+$ , EC, $\gamma$	122 d	<sup>181</sup> W	EC, $e^-$
17 d	<sup>103</sup> Pd	EC, $e^-$	129 d	<sup>170</sup> Tm	$\beta^-$ , $e^-$ , $\gamma$
17.8 d	<sup>74</sup> As	EC, $\beta^+$ , $\beta^-$ , $\gamma$	138 d	<sup>139</sup> Ce	EC, $\gamma$ , $e^-$
18.7 d	<sup>86</sup> Rb	$\beta^-$ , $\gamma$	138.4 d	<sup>210</sup> Po	$\alpha$
24 d, 1.2 m	<sup>234</sup> Th- <sup>234m</sup> Pa	$\beta^-$ , $\gamma$ , $e^-$	~144 d	<sup>159</sup> Dy	EC, $\gamma$ , $e^-$
25 d	<sup>33</sup> P	$\beta^-$	154 d, 17 d	<sup>121m-121</sup> Te	IT, EC, $\gamma$ , $e^-$
27.0 d	<sup>233</sup> Pa	$\beta^-$ , $\gamma$ , $e^-$	163 d	<sup>242</sup> Cm	$\alpha$ , $\gamma$ , $e^-$
27.8 d	<sup>51</sup> Cr	EC, $\gamma$	164 d	<sup>45</sup> Ca	$\beta^-$
31 d	<sup>169</sup> Yb	EC, $\gamma$ , $e^-$	183 d	<sup>195</sup> Au	EC, $\gamma$ , $e^-$
32.5 d	<sup>141</sup> Ce	$\beta^-$ , $\gamma$	206 d	<sup>102</sup> Rh	EC, $\beta^-$ , $\beta^+$
33 d	<sup>84</sup> Rb	$\beta^+$ , $\beta^-$ , EC, $\gamma$	240 d	<sup>153</sup> Gd	EC, $\gamma$ , $e^-$
34 d, 69 m	<sup>129m-129</sup> Te	IT, $\beta^-$ , $\gamma$ , $e^-$	244 d	<sup>65</sup> Zn	$\beta^+$ , EC, $\gamma$
35 d	<sup>37</sup> Ar	EC	250 d	<sup>119m</sup> Sn	IT, $\gamma$ , $e^-$
35 d	<sup>95</sup> Nb	$\beta^-$ , $\gamma$	253 d, 24 s	<sup>110m-110</sup> Ag	$\beta^-$ , $\gamma$ , IT
39.7 d	<sup>103</sup> Ru	$\beta^-$ , $\gamma$	270 d	<sup>57</sup> Co	EC, $\gamma$ , $e^-$
40 d	<sup>105</sup> Ag	EC, $\gamma$ , $e^-$	280 d, 68 m	<sup>68</sup> Ge- <sup>68</sup> Ga	EC, $\beta^+$ , $\gamma$
42.5 d	<sup>181</sup> Hf	$\beta^-$ , $\gamma$	284 d, 17 m	<sup>144</sup> Ce- <sup>144</sup> Pr	$\beta^-$ , $\gamma$ , $e^-$
43 d	<sup>115m</sup> Cd	$\beta^-$ , $\gamma$	313 d	<sup>54</sup> Mn	EC, $\gamma$
44.6 d	<sup>59</sup> Fe	$\beta^-$ , $\gamma$	330 d	<sup>49</sup> V	EC
45.6 d	<sup>237</sup> Pu	EC, $\gamma$ , $e^-$	1.01 y, 30 s	<sup>106</sup> Ru- <sup>106</sup> Rh	$\beta^-$ , $\gamma$
46.5 d	<sup>203</sup> Hg	$\beta^-$ , $\gamma$	1.26 y, 40 s	<sup>109</sup> Cd- <sup>109m</sup> Ag	EC, $\gamma$ , $e^-$ , IT
50 d, 72 s	<sup>114m-114</sup> In	$\beta^-$ , IT, EC, $e^-$	1.4 y	<sup>173</sup> Lu	EC, $\gamma$ , $e^-$
51 d	<sup>89</sup> Sr	$\beta^-$	~1.6 y	<sup>179</sup> Ta	EC
53 d	<sup>7</sup> Be	EC, $\gamma$	1.81 y	<sup>155</sup> Eu	$\beta^-$ , $\gamma$ , $e^-$
58 d	<sup>125m</sup> Te	IT, $e^-$	1.91 y	<sup>228</sup> Th	$\alpha$ , $e^-$
59 d	<sup>91</sup> Y	$\beta^-$ , $\gamma$	700 d	<sup>171</sup> Tm	$\beta^-$ , $\gamma$ , $e^-$
60 d	<sup>125</sup> I	EC, $\gamma$ , $e^-$	2.07 y	<sup>134</sup> Cs	$\beta^-$ , $\gamma$
60.2 d	<sup>124</sup> Sb	$\beta^-$ , $\gamma$	2.60 y	<sup>22</sup> Na	$\beta^+$ , EC, $\gamma$
65 d	<sup>85</sup> Sr	EC, $\gamma$	2.62 y	<sup>147</sup> Pm	$\beta^-$
65 d, 35 d	<sup>95</sup> Zr- <sup>95</sup> Nb	$\beta^-$ , $\gamma$	2.7 y	<sup>125</sup> Sb	$\beta^-$ , $\gamma$
69 d	<sup>188</sup> W	$\beta^-$	2.7 y	<sup>55</sup> Fe	EC
70 d	<sup>183</sup> Re	EC, $\gamma$ , $e^-$	2.9 y	<sup>208</sup> Po	$\alpha$
70 d	<sup>175</sup> Hf	EC, $\gamma$ , $e^-$	3.8 y	<sup>204</sup> Tl	$\beta^-$ , EC
71 d	<sup>58</sup> Co	$\beta^+$ , EC, $\gamma$	5.26 y	<sup>60</sup> Co	$\beta^-$ , $\gamma$
72.4 d	<sup>160</sup> Tb	$\beta^-$ , $\gamma$ , $e^-$	5.5 y	<sup>146</sup> Pm	EC, $\beta^-$ , $\gamma$
74 d	<sup>192</sup> Ir	$\beta^-$ , EC, $\gamma$	5.7 y	<sup>228</sup> Ra	$\beta^-$
75 d	<sup>185</sup> W	$\beta^-$	10.7 y	<sup>133</sup> Ba	EC, $\gamma$ , $e^-$
77.3 d	<sup>56</sup> Co	EC, $\beta^+$ , $\gamma$	10.7 y	<sup>85</sup> Kr	$\beta^-$ , $\gamma$

<sup>a</sup>s, second; m, minute; h, hour; d, day; y, year.

Table 5 (continued)

Half-Life <sup>a</sup>	Radioisotopes	Radiation	Half-Life <sup>a</sup>	Radioisotopes	Radiation
12.3 y	<sup>3</sup> H	$\beta^-$	1600 y	<sup>226</sup> Ra	$\alpha, \gamma$
12.7 y, 16 y	<sup>152</sup> Eu- <sup>154</sup> Eu	$\beta^-, \text{EC}, \gamma, e^-$	$5.73 \times 10^3$ y	<sup>14</sup> C	$\beta^-$
14 y	<sup>113m</sup> Cd	$\beta^-, \gamma, e^-$	$2.0 \times 10^4$ y	<sup>94</sup> Nb	$\beta^-, \gamma$
18 y	<sup>145</sup> Pm	EC, $\gamma, e^-$	$2.44 \times 10^4$ y	<sup>239</sup> Pu	$\alpha, e^-$
18.1 y	<sup>244</sup> Cm	$\alpha, \gamma, e^-$	$3.4 \times 10^4$ y	<sup>231</sup> Pa	$\alpha, \gamma, e^-$
21.3 y	<sup>210</sup> Pb	$\beta^-, \gamma, e^-$	$8 \times 10^4$ y	<sup>230</sup> Th	$\alpha, e^-$
21.8 y	<sup>227</sup> Ac	$\beta^-$	$8 \times 10^4$ y	<sup>59</sup> Ni	$\beta^-$
28.5 y, 64.0 h	<sup>90</sup> Sr- <sup>90</sup> Y	$\beta^-$	$1.62 \times 10^5$ y	<sup>233</sup> U	$\alpha, e^-$
30 y	<sup>207</sup> Bi	EC, $\gamma$	$2.1 \times 10^5$ y	<sup>99</sup> Tc	$\beta^-$
30 y, 2.6 m	<sup>137</sup> Cs- <sup>137m</sup> Ba	$\beta^-, \text{IT}$	$3.0 \times 10^5$ y	<sup>36</sup> Cl	$\beta^-, \text{EC}$
47 y	<sup>44</sup> Ti	EC, $\gamma, e^-$	$7.4 \times 10^5$ y	<sup>26</sup> Al	$\beta^+, \text{EC}, \gamma$
71.7 y	<sup>232</sup> U	$\alpha, e^-$	$2.14 \times 10^6$ y	<sup>237</sup> Np	$\alpha, \gamma, e^-$
87.6 y	<sup>238</sup> Pu	$\alpha, e^-$	$2.6 \times 10^6$ y	<sup>97</sup> Tc	EC
88 y	<sup>148</sup> Gd	$\alpha$	$2.7 \times 10^6$ y	<sup>10</sup> Be	$\beta^-$
~90 y	<sup>151</sup> Sm	$\beta^-, \gamma$	$1.6 \times 10^7$ y	<sup>129</sup> I	$\beta^-, \gamma, e^-$
92 y	<sup>63</sup> Ni	$\beta^-$	$7.13 \times 10^8$ y	<sup>235</sup> U	$\alpha, \gamma, e^-$
~265 y	<sup>39</sup> Ar	$\beta^-$	$1.28 \times 10^9$ y	<sup>40</sup> K	$\beta^-, \text{EC}, \gamma$
433 y	<sup>241</sup> Am	$\alpha, \gamma, e^-$	$4.51 \times 10^9$ y	<sup>238</sup> U	$\alpha, e^-$
$1.2 \times 10^3$ y	<sup>166m</sup> Ho	$\beta^-, \gamma, e^-$	$1.39 \times 10^{10}$ y	<sup>232</sup> Th	$\alpha, e^-$

<sup>a</sup>s, second; m, minute; h, hour; d, day; y, year.

### U.S. Irradiators, Radiation Sources, and Radiation Processing Facilities

Inquiries are often received about the availability of radiation processing facilities; the firms that provide services relating to source design and fabrication are also of interest to radioisotope users. Below is an AEC list of many of the firms that provide these services:

- I** – Irradiator design, engineering, and/or construction
- F** – Source fabrication: cobalt-60 (Co), cesium-137 (Cs), strontium-90 (Sr)
- P** – Producers of cobalt-60 in nuclear reactor
- M** – Machine manufacturers
- S** – Irradiation processing facilities

#### **I,S**

All American Engineering Company  
Development Division  
Post Office Box 1247  
Lancaster Pike and Centre Road  
Wilmington, Delaware 19899  
Phone: (302) 994-0951

#### **I**

Ameray Corporation  
87 Canfield Avenue  
Dover, New Jersey 07801  
Phone: (201) 584-9500

#### **I,F (Co)**

The American Novawood Corporation  
2432 Lakeside Drive  
Lynchburg, Virginia 24501  
Phone: (703) 239-8762

#### **I,F (Co, Cs)**

American Nuclear Corporation  
Post Office Box 426  
Oak Ridge, Tennessee 37830  
Phone: (615) 457-1234

#### **I,M**

Applied Radiation Corporation (ARCO)  
2404 North Main Street  
Walnut Creek, California 94596  
Phone: (415) 935-2250

#### **I**

Associated Engineers & Consultants, Inc.  
(Affiliate of Stone and Webster  
Engineering Corporation)  
975 Stewart Avenue  
Garden City, Long Island, N.Y. 11530  
Phones: (516) 741-4350 or  
NYCity (212) 895-3531

#### **F (Sr)**

Atlantic Research Corporation  
Shirley Highway and Edsall Road  
Alexandria, Virginia 22314  
Phone: (703) 354-3400 Ext. 1011

#### **I,F (Co, Cs)**

Atomchem Corporation  
165 Marine Street  
Farmingdale, Long Island, N.Y. 11735  
Phone: (313) 756-9120

#### **F (Co)**

The Babcock & Wilcox Company  
Washington Operations  
R.C.A. Building  
1725 K Street, N.W.  
Washington, D.C. 20006  
Phone: (202) 296-0390

#### **I**

Bechtel Corporation  
50 Beale Street  
San Francisco, California 94119  
Scientific Development Department  
Phone: (415) 433-4567

#### **I**

Burnes & Roe, Inc.  
700 Kinderkamack Road  
Oradell, New Jersey 07649  
Phone: (201) 265-2000

#### **S**

Columbia Research Corporation  
Post Office Box 485  
Gaithersburg, Maryland 20760  
Phone: (301) 948-2450

**S**

Electronized Chemicals Corporation  
 (Subsidiary of High Voltage Engineering  
 Corporation)  
 South Bedford Street  
 Burlington, Massachusetts 01803  
 Phone: (617) 272-2850

**I**

A. Epstein & Sons, Inc.  
 Engineers & Architects  
 2011 Pershing Road  
 Chicago, Illinois 60609  
 Phone: (312) 847-6000

**S**

FMC Corporation  
 FMC Machinery/Systems Group  
 328 Brokaw Road  
 Box 580  
 Santa Clara, California 95052  
 Phone: (408) 289-0111

**I**

Food Industries Research and Engineering  
 33 South Second Avenue  
 Yakima, Washington 98902  
 Phone: (509) 453-4735

**I**

Office of J. Fruchtbaum  
 1965 Sheridan Drive  
 Buffalo, New York 14223  
 Phone: (716) 877-3350

**I,F (Co, Cs)**

Gamma Industries, Inc.  
 Post Office Box 2543  
 2255 Ted Dunham Street  
 Baton Rouge, Louisiana 70821  
 Phone: (504) 342-7791

**I,F (Co)**

Gamma Process Company, Inc.  
 160 Broadway  
 New York, New York 10038  
 Phone: (212) 233-8570

**M**

General Electric Company  
 X-Ray Department  
 4855 Electric Avenue  
 Milwaukee, Wisconsin 53219  
 Phone: (414) 383-3211

**I,F (Co, Cs, Sr), P (Co)**

General Electric Company  
 Nuclear Energy Division  
 Irradiation Processing Operation  
 Vallecitos Nuclear Center  
 Vallecitos Road  
 Pleasanton, California 94566  
 Attn: Program Manager, Applications Engineering  
 Phone: (415) 862-2211

**I,S**

High Energy Processing Corporation  
 Industrial Park  
 New Bedford, Massachusetts 02745  
 Phone: (617) 995-9840

**M,S**

High Voltage Engineering Corporation  
 Industrial Division  
 South Bedford Street  
 Burlington, Massachusetts 01803  
 Phone: (617) 272-1313

**I**

Holmes & Narver, Inc.  
 828 South Figueroa Street  
 Los Angeles, California 90017  
 Nuclear Engineering  
 Phone: (213) 627-4377

**I**

Irradco, Inc.  
 Post Office Box 2167  
 Allentown, Pennsylvania 18105  
 Phone: (215) 395-3391

**I,S**

Isotopes, Inc.  
 A Teledyne Company  
 Westwood Laboratories  
 50 Van Buren Avenue  
 Westwood, New Jersey 07675  
 Attn: Manager, Industrial Applications  
 Phone: (201) 664-7070

**I**

The Kuljian Corporation  
 1200 North Broad Street  
 Philadelphia, Pennsylvania 19121  
 Chief Nuclear Engineer  
 Phone: (215) 232-9000

**I,F (Co, Cs), S**

Lockheed Georgia Company  
Nuclear Products  
Department 69-12, Zone 3  
Marietta, Georgia 30060  
Phone: (404) 424-7736

**F (Cs)**

3M Company  
3M Center  
St. Paul, Minnesota 55101  
Nuclear Products, TCAAP-675  
Phone: (612) 631-2420

**I**

Charles T. Main, Inc.  
441 Stuart Street  
Boston, Massachusetts 02116  
Phone: (617) 262-3200

**I**

National Lead Company  
Nuclear Division  
Wilmington Plant  
Post Office Box 2031  
Wilmington, Delaware 19899  
Phone: (302) 656-1661

**I,F (Co), S**

Nuclear Materials & Equipment Corporation  
609 Warren Avenue  
Apollo, Pennsylvania 15613  
Attn: Manager, Radiation Process Development  
Phone: (412) 472-8411

**I**

Nuclear Technology Corporation  
116 Main Street  
White Plains, New York 10601  
Phone: (914) 949-5660

**I,F (Co), S**

Neutron Products, Inc.  
Post Office Box 95  
Dickerson, Maryland 20753  
Phone: (301) 349-5660

**I**

Oak Ridge Atom Industries, Inc.  
Post Office Box 429  
500 Elza Drive  
Oak Ridge, Tennessee 37830  
Phone: (615) 482-1761

**F (Cs, Sr), P (Co)**

Oak Ridge National Laboratory  
Post Office Box X  
Oak Ridge, Tennessee 37830  
Attn: Supervisor, Isotopes Sales Department  
Phone: (615) 483-8611 Ext. 3-6661

**M,S**

Picker X-Ray Manufacturing Division  
Picker Corporation  
595 Miner Road  
Highland Heights, Ohio 44143  
Attn: Supervisor, Isotope Facility

**I,S**

Radiation Facilities, Inc.  
63 Dell Glen Avenue  
Lodi, New Jersey 07644  
Phone: (201) 478-1200

**I,F (Co, Cs), M,S**

Radiation Machinery Corporation  
1280 Route 46  
Parsippany, New Jersey 07054  
Attn: Vice President, Marketing  
Phone: (201) 335-6780

**I**

Reynolds, Smith and Hills  
Post Office Box 4850  
4019 Boulevard Center Drive  
Jacksonville, Florida 32201  
Phone: (305) 359-2011

**I,M**

Stearns-Roger Corporation  
660 Bannock Street  
Post Office Box 5888  
Denver, Colorado 80217  
Phone: (303) 222-8484 Ext. 4522

**I,F (Co)**

Technical Operations, Inc.  
Radiation Products Division  
South Avenue  
Burlington, Massachusetts 01803  
Phone: (617) 272-2000

**I,S**

Todd Shipyards Corporation  
Nuclear Division  
Post Office Box 1600  
Galveston, Texas 77550  
Phone: (713) SH 4-5331

**I**

United Nuclear Corporation  
 Grasslands Road  
 Elmsford, New York 10523  
 Attn: Manager, Marketing  
 Phone: (914) 592-9000 Ext. 265

**M**

Varian Associates  
 611 Hansen  
 Palo Alto, California 94304  
 Attn: General Manager, Radiation Division  
 Phone: (415) 326-4000

**M**

Westinghouse Electric Corporation  
 X-Ray Division  
 2519 Wilkens Avenue  
 Baltimore, Maryland 21203  
 Attn: Marketing Department  
 Phone: (301) 233-2300

**I**

Windsor Nuclear, Inc.  
 300 Governor's Highway  
 South Windsor, Connecticut 06074  
 Attn: Plant Manager  
 Phone: (203) 389-7541

### Radioisotopes for Educational Purposes

Teachers and students sometimes find it difficult to obtain small quantities of radioisotopes for experiments. In July 1968 the USAEC contacted all of the commercial producers of radioisotopes in the United States and asked if they wished to be included on a list of suppliers of small quantities of isotopes for educational purposes. The following firms answered:

Amersham/Searle Corp. 2000 Nuclear Drive Des Plaines, Illinois 60018	Catalog
Atomic Corporation of America 7901 San Fernando Road Sun Valley, California 91352	Catalog
Brinkman Instruments, Inc. Cantiague Road Westbury, New York 11590	Catalog
Calatomic P.O. Box 54282 Terminal Annex Los Angeles, California 90054	Catalog
Cambridge Nuclear Corporation 131 Portland Street Cambridge, Massachusetts 02139	Minimum order \$6.00 with \$1.00 delivery charge Catalog
Eberline Instrument Corporation P.O. Box 2108 Santa Fe, New Mexico 87501	Will supply any isotope requested Catalog
General Radioisotope Processing Corporation 3120 Crow Canyon Road San Ramon, California 94583	Catalog

ICN  
Nuclear Science Division  
P.O. Box 10901  
Pittsburgh, Pennsylvania 15236

Minimum price \$34--\$45  
Catalog

The Matheson Company  
P.O. Box 85  
East Rutherford, New Jersey 07073

A source for gas mixtures containing isotopes of  
 $^{85}\text{Kr}$ ,  $^{14}\text{C}$ ,  $^3\text{H}$ , and  $^{35}\text{S}$  for tracing and cali-  
brating work

New England Nuclear Corporation  
575 Albany Street  
Boston, Massachusetts 02118

Nuclear Equipment Chemical Corporation  
145 Florida Street  
Farmingdale, New York 11735

Catalog

Nuclear Supplies, Inc.  
P.O. Box 312  
Encino, California 91316

Minimum order \$20.00  
Catalog

Radiation Materials Corporation  
124 Calvary Street  
Waltham, Massachusetts 02154

Tracerlab  
Source Department  
1601 Trapelo Road  
Waltham, Massachusetts 02154

Minimum order \$10.00

## AVAILABILITY AND SHIPPING INFORMATION

Generally, radioisotopes having half-lives of less than one week are shipped by air; longer half-life materials are shipped by railway express or motor freight. Alternative methods may be used at the request of the customer. Postal regulations are such that only very small amounts of activity can be sent by mail, therefore, mail service is seldom used. Shipments are usually made freight collect, f.o.b. at point of delivery to a common carrier.

### Containers

Two types of containers are used routinely in making shipments of radioactive materials: the heavy, shielded containers (Figs. 5–10) that must be returned to the supplier and the nonreturnable lightweight containers (Figs. 11–12) which are used for only one shipment. At present, 90% of the shipments are made in disposable containers. Up to 0.625 in. of lead for shielding may be included in this type of container.

When the nature of the material makes it impossible for a supplier's container to be used, the customer must supply the container. All customers' containers must conform to the existing Department of Transportation regulations, and they must be suitable for use with the supplier's equipment. Therefore, before fabrication is started, the design should be submitted to the supplier for review.

Container designs that require approval by the USAEC in accordance with Title 10, *Code of Federal Regulations*, Part 71, must have this approval prior to submission to the supplier. After the design has been reviewed by the supplier, it should be submitted for approval to the Hazardous Materials Regulation Board, Department of Transportation, Washington, D.C. 20590. Upon approval by the Department of Transportation, the container is assigned a special permit number which must be displayed on the outside of the container. Containers that do not carry such a permit number may not be shipped.

PHOTO 93388

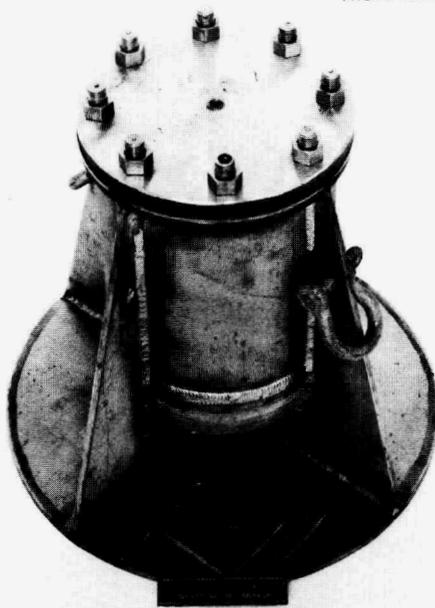


Fig. 5. Shipping Cask Suitable for up to 150 W (thermal) of Solid Nonfissile Radioactive Material and up to 10 Ci of Liquid.

PHOTO 93389



Fig. 6. Shipping Container Meeting the Requirements for Type B Quantities of Radioactive Gas.

PHOTO 93390

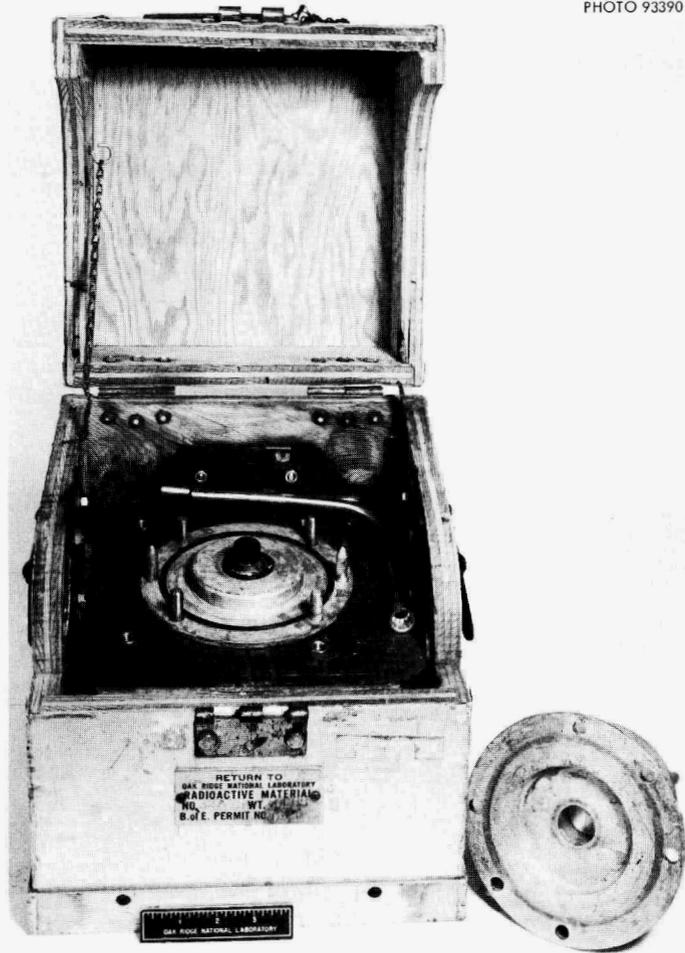


Fig. 7. Standard Returnable Container for Shipping Type A Quantities.

PHOTO 93393



Fig. 8. Shipping Container Approved for 200 W (thermal) of Solid Nonfissile Radioactive Material.

PHOTO 93394

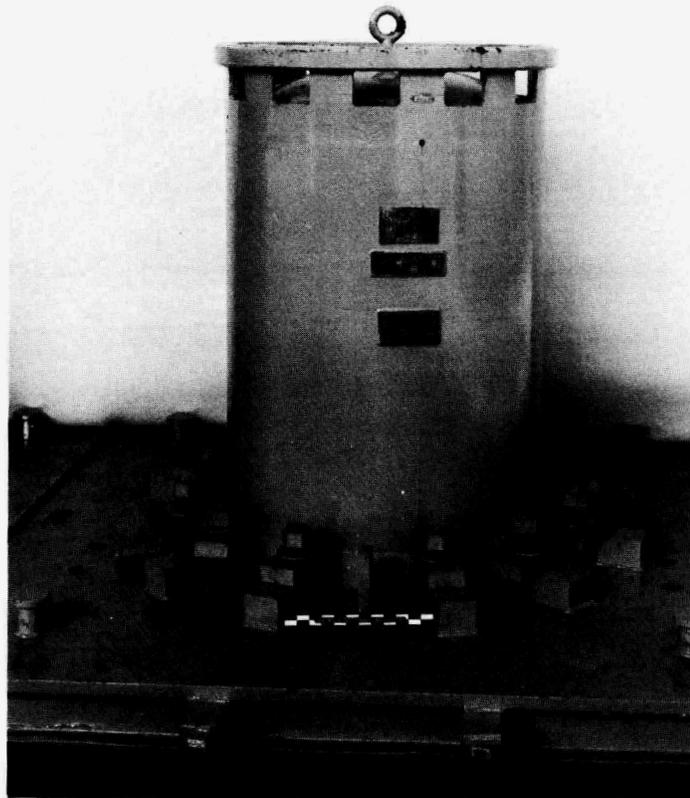


Fig. 9. Shipping Cask Approved for up to 200 kCi of Solid Nonfissile Radioactive Material That Meets the Definition of "Special Form."

PHOTO 93395

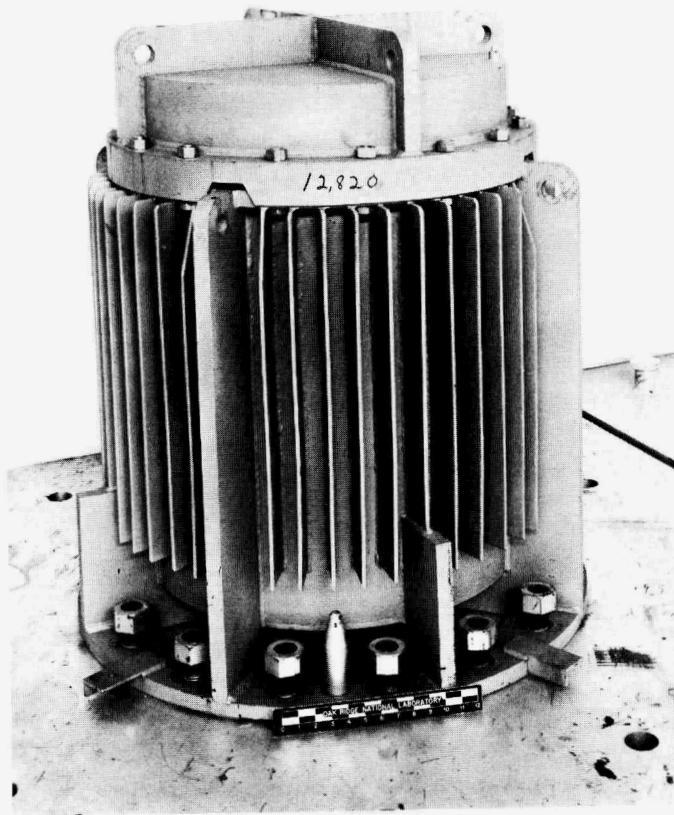


Fig. 10. Shipping Container Approved for up to 400 kCi of Solid Nonfissile Radioactive Material.

PHOTO 93391



Fig. 11. Standard Nonreturnable Shipping Package for Type A Quantities.

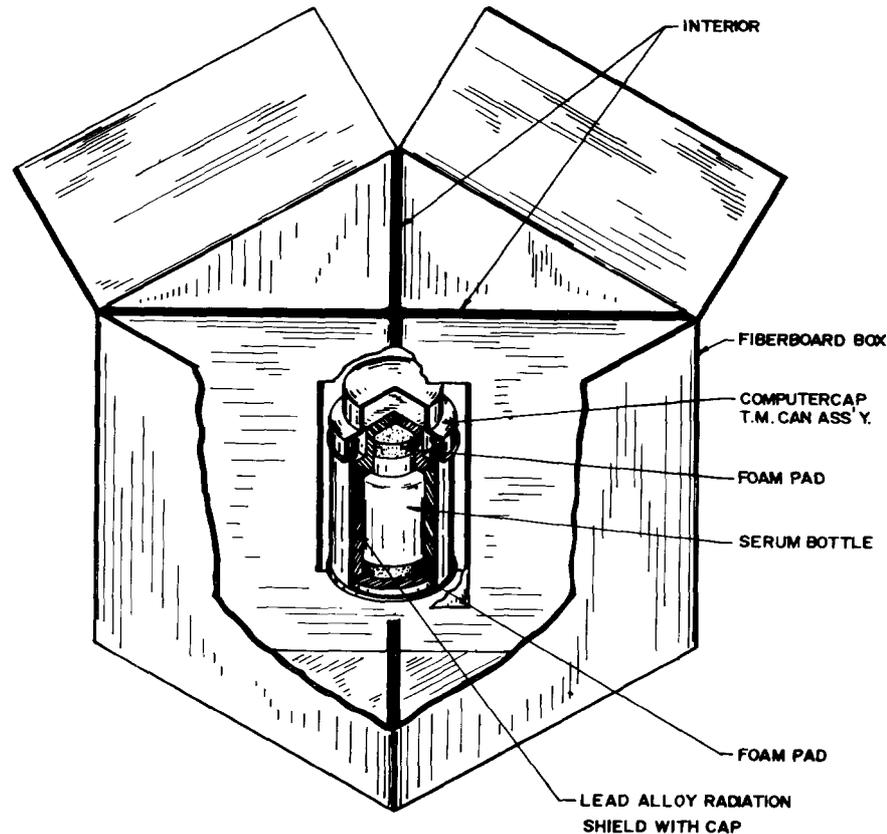


Fig. 12. Union Carbide Corporation (Neisler) Computercap<sup>TM</sup> Radiopharmaceutical Shipping Package.

### Radiation and Contamination from Packaged Radioisotopes

After radioactive material has been packaged for shipping, the container is checked for outside radiation to ensure that the package meets USAEC, Department of Transportation, Civil Aeronautics Board, and Coast Guard regulations. There must be no more than 200 mR/h at the surface of the container and no more than 10 mR/h at 1 m from the surface. Transferable contamination on the surface of the package is determined by wipes or smears and is subject to pertinent regulations. These values are usually listed on the packing sheet accompanying the shipment.

Although every effort is made to have bottles or other inner containers as clean as possible, they should be handled as though they were contaminated. Proper radiological safety procedures should be followed, and equipment for handling contamination should be used at all times.

### Responsibility During Shipment

The responsibility of the supplier for damage to shipments ordinarily ends when the shipment is delivered to a common carrier, and claims for damages in transit usually will not be considered by the supplier.

### License Requirements

The procurement, delivery, possession, transfer, and disposal of radioisotopes in the United States are governed by federal or state regulations or both. To obtain radioactive material from a supplier, the customer must first procure a license either from the USAEC or from the appropriate state agency if the customer is in a license-agreement state, that is, a state which has assumed the responsibility of controlling the distribution, handling, and use of radioactive materials. It is not a function of the supplier to approve or disapprove such licenses. Inquiries about licensing should be directed to Isotopes Branch, Division of Materials Licensing, U.S. Atomic Energy Commission, Washington, D.C. 20545 (telephone: 301-973-7491). Agencies to be contacted in license-agreement states are:

#### Alabama

Alabama Department of Public Health  
Division of Radiological Health  
State Office Building, Room 313  
Montgomery, Alabama 36104

#### Arizona

Arizona Atomic Energy Commission  
40 East Thomas Road, Suite 107  
Phoenix, Arizona 85012

#### Arkansas

Arkansas State Board of Health  
Division of Radiological Health  
Little Rock, Arkansas 72200

#### California

Department of Public Health  
Bureau of Radiological Health  
2151 Berkeley Way  
Berkeley, California 94704

#### Colorado

Division of Air, Occupational, and  
Radiation Hygiene  
Colorado Department of Public Health  
4210 East 11th Avenue  
Denver, Colorado 80220

#### Florida

Florida State Board of Health  
Division of Radiological and Occupational Health  
P.O. Box 210  
Jacksonville, Florida 32201

#### Idaho

Radiological Health Section  
Idaho Department of Health  
State House  
Boise, Idaho 83707

#### Kansas

Kansas State Board of Health  
Environmental Health Services  
Topeka, Kansas 66612

#### Kentucky

Kentucky State Department of Health  
Radiological Health Program  
275 East Main Street  
Frankfort, Kentucky 40601

#### Louisiana

Division of Radiation Control  
Louisiana Board of Nuclear Energy  
P.O. Box 44033  
Capitol Station  
Baton Rouge, Louisiana 70804

#### Mississippi

Mississippi State Board of Health  
Radiological Health Unit  
Jackson, Mississippi 39205

#### Nebraska

Nebraska State Department of Health  
Radiological Health  
Lincoln, Nebraska 68509

#### New Hampshire

New Hampshire Department of Health and Welfare  
Division of Public Health Services  
Radiation Control Agency  
61 South Spring Street  
Concord, New Hampshire 03301

#### New York

New York State Office of Atomic and Space  
Development  
P.O. Box 7036  
Albany, New York 12225

**North Carolina**

North Carolina State Board of Health  
 State Radiation Protection Program  
 Raleigh, North Carolina 27602

**Oregon**

Oregon State Board of Health  
 Radiological Health Section  
 P.O. Box 231  
 Portland, Oregon 97207

**Tennessee**

Tennessee Department of Public Health  
 Industrial Hygiene Service  
 Cordell Hull State Office Building  
 Nashville, Tennessee 37219

**Texas**

Texas State Department of Health  
 Division of Occupational Health and  
 Radiation Control  
 Austin, Texas 78756

**Washington**

Washington State Department of Health  
 Division of Environmental Health  
 Air Quality and Radiation Control Section  
 1510 Smith Tower  
 Seattle, Washington 98104

**Foreign Sales**

Radioisotopes for elements with atomic numbers 3 through 83 (lithium through bismuth) may be shipped to free-world destinations outside the United States without prior approval from the USAEC provided the shipment is made directly to the destination. Export agencies, other organizations, or middlemen arranging such shipments must obtain a license if they handle the material. However, shipments can usually be made directly from the supplier (by air or surface) to the destination without being handled by intermediaries.

Radioisotope orders for non-free-world destinations and all tritium (except tritium targets) and transuranium-element orders (except  $^{241}\text{Am}$ ) must be submitted on form AEC-391 to the Division of State and Licensee Relations, U.S. Atomic Energy Commission, Washington, D.C. 20545. A statement of end use must accompany each order before approval for shipment can be made.

**Products Withdrawn from Routine USAEC Distribution**

The policy of the U.S. Atomic Energy Commission is to withdraw from the production and sale of radioisotopes that are commercially available. Thus, many isotopes formerly available from Oak Ridge National Laboratory and other USAEC laboratories have been withdrawn.

Lists of commercial producers and distributors of radioisotopes are contained in the following publications:

*The Isotope Index*  
 360 pp., \$10.00

Scientific Equipment Company  
 P.O. Box 19086  
 Indianapolis, Indiana 46219

*International Directory of Isotopes*  
 487 pp., \$9.00

National Agency for International Publications, Inc.  
 317 East 34th Street  
 New York, New York 10016

The exact AEC policy for transfer of production and distribution to private industry is reproduced below (reprinted from the *Federal Register*, March 9, 1965):

## ATOMIC ENERGY COMMISSION

### Policies and Procedures for Transfer of Commercial Radioisotope Production and Distribution to Private Industry

#### Statement of Policy

Since 1946, the United States Atomic Energy Commission has produced radioisotopes in its own facilities and distributed them for governmental and private use. In recent years, private facilities have become available which are capable of producing and processing some of these radioisotopes. The Commission's policy is to refrain from competing with private sources of materials when they are reasonably available commercially. Accordingly, over the past years the Commission has discontinued production and distribution of selected types, quantities and qualities of radioisotopes and related services as these have become available from private sources.

There is currently a rapidly growing industrial interest in undertaking private production and distribution of increasing numbers of radioisotopes presently being distributed by the Commission. It therefore wishes to reaffirm its policy to transfer its commercial radioisotope production and distribution activities to private industry as rapidly as possible consistent with the national interest. To provide for the orderly transfer to private operation, the Commission developed proposed policies and procedures for effecting such transfer. On September 16, 1964, the Commission published in the *Federal Register* a request for public comment on the proposed policies and procedures.

Interested persons were requested to direct their comments to the Secretary, United States Atomic Energy Commission, Washington, D.C., 20545, within 60 days from that date. The Commission has now adopted policies and procedures for the transfer of commercial AEC radioisotope production and distribution activities to private industry, effective immediately upon the publication of this notice in the *Federal Register*.

#### Policies and Procedures for Transfer of Commercial AEC Radioisotope Production and Distribution Activities to Private Industry

The policies and procedures encompass:

- a. The establishment of guidelines governing AEC withdrawal from production and distribution of particular radioisotopes, either voluntarily or upon petition of a private organization.
- b. The establishment of a petition procedure by which private organizations may formally request AEC withdrawal from the production and distribution of particular radioisotopes.
- c. The application of AEC radioisotope pricing policy.
- d. The AEC position with respect to its conduct of radioisotope production technology research and development on those radioisotopes from which it has withdrawn from production and distribution.

**Withdrawal guidelines.** 1. The AEC will voluntarily withdraw from the commercial production and distribution of particular radioisotopes whenever it determines that such radioisotopes are reasonably available from commercial sources.

2. The AEC will withdraw from the commercial production and distribution of particular radioisotopes on petition from a private organization based upon a demonstrable private capability and encompassing the following but recognizing that all these factors need not be completely satisfied:

- a. There is effective competition in the production and distribution of the radioisotopes in question; however, a single source of supply under certain conditions may be acceptable (e.g., very limited market). Foreign producers will be accepted in determining effective competition provided they are actively marketing the radioisotopes in the U.S.
- b. There is assurance that the private producers will not discontinue the venture in a manner that would adversely affect the public interest, to the extent resumption of production by AEC would involve a significant delay.
- c. The proposed private radioisotope prices are reasonable and consistent with encouragement of research and development and use.

**Government isotope requirements.** It is the Atomic Energy Commission's policy to obtain radioisotopes from commercial sources where it has formally withdrawn from the production and distribution of those radioisotopes. However, the AEC maintains the right to produce an isotope for Government use in those circumstances where the Government is a substantial user, or the use is of special programmatic interest to the AEC, and, where procurement from industry would result in significantly higher cost to the Government.

**Filing a petition.** 1. An organization requesting that the AEC withdraw from the production and distribution of a particular radioisotope may submit a formal petition to this effect. Such a petition should contain sufficient evidence to demonstrate adequate technical, financial and managerial resources, as well as seriousness of intent.

2. The petition should include:

- a. Product specifications to show evidence of their comparability to AEC products or adequacy to meet user demands.
- b. Estimate of current demand. (The petitioner's production capabilities in conjunction with that of other suppliers should be adequate to meet this demand.)
- c. The petitioning organization's production, processing and distribution capability, including identification of the production facilities (e.g., nuclear reactors and/or cyclotrons) available to it and the extent of commitment upon them in relation to market requirements.
- d. Price schedule.
- e. Delivery schedule.
- f. Proposed date of AEC withdrawal.

The AEC may request additional information if the above information is inadequate for AEC to make a finding.

3. Upon making a finding favorable to the petition, the AEC will publish for public comment:

a. The private organization's petition or a summary thereof, exclusive of company confidential information, and will designate the place where a copy of the petition, exclusive of company confidential information, may be seen. (The petitioner should identify those portions of his petition which contain company confidential information; however, the information published must be sufficient to permit meaningful public comment.)

b. A notice of AEC's intent to withdraw. AEC will make a final decision on the withdrawal petition upon receipt and evaluation of public comment.

4. Upon making an unfavorable decision on a petition, either prior to or subsequent to receipt of public comment, AEC will inform the petitioning organization of the reasons for its decision.

5. When AEC determines to withdraw voluntarily from the commercial production and distribution of particular radioisotopes, it will similarly publish a notice of such intent for public comment.

**AEC radioisotope prices.** 1. AEC radioisotope prices will be established to provide reasonable compensation to the Government (which ordinarily will be the higher of AEC full cost recovery or reasonable commercial rates) unless this would significantly interfere with (a) research and development and use or (b) encouragement of private sources of supply. In individual cases, if (a) and (b) cannot be equally accommodated, greater weight will be given to encouragement of research and development and use.

2. The AEC will publish a 30 day prior notice of proposed price changes, including the reasons for the proposed changes.

3. The AEC will not change the price of a radioisotope during the period it is reviewing a petition for AEC withdrawal from production and distribution of that isotope.

**AEC radioisotope production technology research.** 1. AEC will place the conduct of radioisotope production technology research and development it deems necessary to be carried out with groups most qualified to perform such work, whether these be AEC facilities or private organizations.

2. AEC will conduct or support production technology research and development on radioisotopes from which it has withdrawn as it deems necessary, but only to the extent that AEC has satisfied itself that industry is unable, is unwilling or simply is not carrying out such work adequately or where it determines that direct AEC effort is necessary in the interest of the atomic energy program.

(Sec. 161, 68 Stat. 948; 42 U.S.C. 2201)

Dated at Washington, D.C., this 2d day of March 1965.

For the Atomic Energy Commission.

W. B. McCool,  
Secretary

[F.R. Doc. 65-2382; Filed, Mar. 8, 1965; 8:46 a.m.]

### Generally Licensed Quantities and Exempt Concentrations of Radioisotopes

The USAEC and the regulatory states maintain control of all by-product material, that is, all man-made radioactive material and all enriched natural radioactive material. Rules and regulations require that specific licenses be issued to named persons only after applications are filed under the provisions of Title 10, *Code of Federal Regulations*, Parts 30 to 36. However, in order to encourage the use of radioisotopes, the USAEC has set up two ways whereby radioisotopes can be obtained and used without going through the formality of acquiring a specific license. Under the *exempt concentrations* rule, certain radioisotopes can be obtained as long as the radioactivity does not exceed a specific concentration. Alternatively, under the *generally licensed quantities* rule, anyone can obtain certain radioisotopes in any concentration as long as the radioactivity does not exceed a certain quantity (see Table 6).

Table 6. Exempt Radioisotopes

Element	Isotopes	Generally Licensed Quantities <sup>a</sup> (μCi)	Exempt Concentrations	
			Gas (μCi/ml)	Solid (μCi/g) or Liquid (μCi/ml)
Antimony	<sup>122</sup> Sb			3 × 10 <sup>-4</sup>
	<sup>124</sup> Sb	1		2 × 10 <sup>-4</sup>
	<sup>125</sup> Sb			1 × 10 <sup>-3</sup>
Argon	<sup>37</sup> Ar		1 × 10 <sup>-3</sup>	
	<sup>41</sup> Ar		4 × 10 <sup>-7</sup>	
Arsenic	<sup>73</sup> As			5 × 10 <sup>-3</sup>
	<sup>74</sup> As			5 × 10 <sup>-4</sup>
	<sup>76</sup> As	10		2 × 10 <sup>-4</sup>
	<sup>77</sup> As	10		8 × 10 <sup>-4</sup>
Barium	<sup>131</sup> Ba			2 × 10 <sup>-3</sup>
	<sup>140</sup> Ba	1		3 × 10 <sup>-4</sup>

<sup>a</sup>Amounts listed are for unsealed sources. Amounts permitted for sealed sources are slightly higher for most radioisotopes.

Table 6 (continued)

Element	Isotopes	Generally Licensed Quantities <sup>a</sup> ( $\mu\text{Ci}$ )	Exempt Concentrations	
			Gas ( $\mu\text{Ci}/\text{ml}$ )	Solid ( $\mu\text{Ci}/\text{g}$ ) or Liquid ( $\mu\text{Ci}/\text{ml}$ )
Beryllium	<sup>7</sup> Be	50		$2 \times 10^{-2}$
Bismuth	<sup>206</sup> Bi			$4 \times 10^{-4}$
Bromine	<sup>82</sup> Br		$4 \times 10^{-7}$	$3 \times 10^{-3}$
Cadmium	<sup>109</sup> Cd	10		$2 \times 10^{-3}$
	<sup>115m</sup> Cd			$3 \times 10^{-4}$
	<sup>115</sup> Cd			$3 \times 10^{-4}$
Calcium	<sup>45</sup> Ca	10		$9 \times 10^{-5}$
	<sup>47</sup> Ca			$5 \times 10^{-4}$
Carbon	<sup>14</sup> C	50	$1 \times 10^{-6}$	$8 \times 10^{-3}$
Cerium	<sup>141</sup> Ce			$9 \times 10^{-4}$
	<sup>143</sup> Ce			$4 \times 10^{-4}$
	<sup>144</sup> Ce	1		$1 \times 10^{-4}$
Cesium	<sup>131</sup> Cs			$2 \times 10^{-2}$
	<sup>134m</sup> Cs			$6 \times 10^{-2}$
	<sup>134</sup> Cs			$9 \times 10^{-5}$
	<sup>137</sup> Cs	1		
Chlorine	<sup>36</sup> Cl	1		
	<sup>38</sup> Cl		$9 \times 10^{-7}$	$4 \times 10^{-3}$
Chromium	<sup>51</sup> Cr	50		$2 \times 10^{-2}$
Cobalt	<sup>57</sup> Co			$5 \times 10^{-3}$
	<sup>58</sup> Co			$1 \times 10^{-3}$
	<sup>60</sup> Co	1		$5 \times 10^{-4}$
Copper	<sup>64</sup> Cu	50		$3 \times 10^{-3}$
Dysprosium	<sup>165</sup> Dy			$4 \times 10^{-3}$
	<sup>166</sup> Dy			$4 \times 10^{-4}$
Erbium	<sup>169</sup> Er			$9 \times 10^{-4}$
	<sup>171</sup> Er			$1 \times 10^{-3}$
Europium	<sup>152</sup> Eu			$6 \times 10^{-4}$
	<sup>154</sup> Eu	1		
	<sup>155</sup> Eu			$2 \times 10^{-3}$
Fluorine	<sup>18</sup> F	50	$2 \times 10^{-6}$	$8 \times 10^{-3}$
Gadolinium	<sup>153</sup> Gd			$2 \times 10^{-3}$
	<sup>159</sup> Gd			$8 \times 10^{-4}$
Gallium	<sup>72</sup> Ga	10		$4 \times 10^{-4}$
Germanium	<sup>71</sup> Ge	50		$2 \times 10^{-2}$
Gold	<sup>196</sup> Au			$2 \times 10^{-3}$
	<sup>198</sup> Au	10		$5 \times 10^{-4}$
	<sup>199</sup> Au	10		$2 \times 10^{-3}$

<sup>a</sup>Amounts listed are for unsealed sources. Amounts permitted for sealed sources are slightly higher for most radioisotopes.

Table 6 (continued)

Element	Isotopes	Generally Licensed Quantities <sup>a</sup> ( $\mu\text{Ci}$ )	Exempt Concentrations	
			Gas ( $\mu\text{Ci/ml}$ )	Solid ( $\mu\text{Ci/g}$ ) or Liquid ( $\mu\text{Ci/ml}$ )
Hafnium	$^{181}\text{Hf}$			$7 \times 10^{-4}$
Hydrogen	$^3\text{H}$	250	$5 \times 10^{-6}$	$3 \times 10^{-2}$
Indium	$^{113m}\text{In}$			$1 \times 10^{-2}$
	$^{114m}\text{In}$			$2 \times 10^{-4}$
Iodine	$^{126}\text{I}$		$3 \times 10^{-9}$	$2 \times 10^{-5}$
	$^{131}\text{I}$	10	$3 \times 10^{-9}$	$2 \times 10^{-5}$
	$^{132}\text{I}$		$8 \times 10^{-8}$	$6 \times 10^{-4}$
	$^{133}\text{I}$		$1 \times 10^{-8}$	$7 \times 10^{-5}$
	$^{134}\text{I}$		$2 \times 10^{-7}$	$1 \times 10^{-3}$
Iridium	$^{190}\text{Ir}$			$2 \times 10^{-3}$
	$^{192}\text{Ir}$	10		$4 \times 10^{-4}$
	$^{194}\text{Ir}$			$3 \times 10^{-4}$
Iron	$^{55}\text{Fe}$	50		$8 \times 10^{-3}$
	$^{59}\text{Fe}$	1		$6 \times 10^{-4}$
Krypton	$^{85m}\text{Kr}$		$1 \times 10^{-6}$	
	$^{85}\text{Kr}$		$3 \times 10^{-6}$	
Lanthanum	$^{140}\text{La}$	10		$2 \times 10^{-4}$
Lead	$^{203}\text{Pb}$			$4 \times 10^{-3}$
Lutetium	$^{177}\text{Lu}$			$1 \times 10^{-3}$
Manganese	$^{52}\text{Mn}$	1		$3 \times 10^{-4}$
	$^{54}\text{Mn}$			$1 \times 10^{-3}$
	$^{56}\text{Mn}$	50		$1 \times 10^{-3}$
Mercury	$^{197m}\text{Hg}$			$2 \times 10^{-3}$
	$^{197}\text{Hg}$			$3 \times 10^{-3}$
	$^{203}\text{Hg}$			$2 \times 10^{-4}$
Molybdenum	$^{99}\text{Mo}$	10		$2 \times 10^{-3}$
Neodymium	$^{147}\text{Nd}$			$6 \times 10^{-4}$
	$^{149}\text{Nd}$			$3 \times 10^{-3}$
Nickel	$^{59}\text{Ni}$	1		
	$^{63}\text{Ni}$	1		
	$^{65}\text{Ni}$			$1 \times 10^{-3}$
Niobium	$^{95}\text{Nb}$	10		$1 \times 10^{-3}$
	$^{97}\text{Nb}$			$9 \times 10^{-3}$
Osmium	$^{185}\text{Os}$			$7 \times 10^{-4}$
	$^{191m}\text{Os}$			$3 \times 10^{-2}$
	$^{191}\text{Os}$			$2 \times 10^{-3}$
	$^{193}\text{Os}$			$6 \times 10^{-4}$
Palladium	$^{103}\text{Pd}$	50		$3 \times 10^{-3}$
	$^{109}\text{Pd}$	10		$9 \times 10^{-4}$

<sup>a</sup>Amounts listed are for unsealed sources. Amounts permitted for sealed sources are slightly higher for most radioisotopes.

Table 6 (continued)

Element	Isotopes	Generally Licensed Quantities <sup>a</sup> (μCi)	Exempt Concentrations	
			Gas (μCi/ml)	Solid (μCi/g) or Liquid (μCi/ml)
Phosphorus	<sup>32</sup> P	10		2 × 10 <sup>-4</sup>
Platinum	<sup>191</sup> Pt			1 × 10 <sup>-3</sup>
	<sup>193m</sup> Pt			1 × 10 <sup>-2</sup>
	<sup>197m</sup> Pt			1 × 10 <sup>-2</sup>
	<sup>197</sup> Pt			1 × 10 <sup>-3</sup>
Polonium	<sup>210</sup> Po	0.1		
Potassium	<sup>42</sup> K	10		3 × 10 <sup>-3</sup>
Praseodymium	<sup>142</sup> Pr			3 × 10 <sup>-4</sup>
	<sup>143</sup> Pr	10		
Promethium	<sup>147</sup> Pm	10		2 × 10 <sup>-3</sup>
	<sup>149</sup> Pm			4 × 10 <sup>-4</sup>
Rhenium	<sup>183</sup> Re			6 × 10 <sup>-3</sup>
	<sup>186</sup> Re	10		9 × 10 <sup>-4</sup>
	<sup>188</sup> Re			6 × 10 <sup>-4</sup>
Rhodium	<sup>103m</sup> Rh			1 × 10 <sup>-1</sup>
	<sup>105</sup> Rh	10		1 × 10 <sup>-3</sup>
Rubidium	<sup>86</sup> Rb	10		7 × 10 <sup>-4</sup>
Ruthenium	<sup>97</sup> Ru			4 × 10 <sup>-3</sup>
	<sup>103</sup> Ru			8 × 10 <sup>-4</sup>
	<sup>105</sup> Ru			1 × 10 <sup>-3</sup>
	<sup>106</sup> Ru	1		1 × 10 <sup>-4</sup>
Samarium	<sup>153</sup> Sm	10		8 × 10 <sup>-4</sup>
Scandium	<sup>46</sup> Sc	1		4 × 10 <sup>-4</sup>
	<sup>47</sup> Sc			9 × 10 <sup>-4</sup>
	<sup>48</sup> Sc			3 × 10 <sup>-4</sup>
Selenium	<sup>75</sup> Se			3 × 10 <sup>-3</sup>
Silicon	<sup>31</sup> Si			9 × 10 <sup>-3</sup>
Silver	<sup>105</sup> Ag	1		1 × 10 <sup>-3</sup>
	<sup>110m</sup> Ag			3 × 10 <sup>-4</sup>
	<sup>111</sup> Ag	10		4 × 10 <sup>-4</sup>
Sodium	<sup>22</sup> Na	10		
	<sup>24</sup> Na	10		2 × 10 <sup>-3</sup>
Strontium	<sup>89</sup> Sr	1		1 × 10 <sup>-4</sup>
	<sup>90</sup> Sr	0.1		
	<sup>91</sup> Sr			7 × 10 <sup>-4</sup>
	<sup>92</sup> Sr			7 × 10 <sup>-4</sup>

<sup>a</sup>Amounts listed are for unsealed sources. Amounts permitted for sealed sources are slightly higher for most radioisotopes.

Table 6 (continued)

Element	Isotopes	Generally Licensed Quantities <sup>a</sup> ( $\mu\text{Ci}$ )	Exempt Concentrations	
			Gas ( $\mu\text{Ci}/\text{ml}$ )	Solid ( $\mu\text{Ci}/\text{g}$ ) or Liquid ( $\mu\text{Ci}/\text{ml}$ )
Sulfur	$^{35}\text{S}$	50	$9 \times 10^{-8}$	$6 \times 10^{-4}$
Tantalum	$^{182}\text{Ta}$	10		$4 \times 10^{-4}$
Technetium	$^{96m}\text{Tc}$			$1 \times 10^{-1}$
	$^{96}\text{Tc}$	1		$1 \times 10^{-3}$
	$^{99}\text{Tc}$	1		
Tellurium	$^{125m}\text{Te}$			$2 \times 10^{-3}$
	$^{127m}\text{Te}$			$6 \times 10^{-4}$
	$^{127}\text{Te}$	10		$3 \times 10^{-3}$
	$^{129m}\text{Te}$			$3 \times 10^{-4}$
	$^{129}\text{Te}$	1		
	$^{131m}\text{Te}$			$6 \times 10^{-4}$
Terbium	$^{132}\text{Te}$			$3 \times 10^{-4}$
	$^{160}\text{Tb}$			$4 \times 10^{-4}$
Thallium	$^{200}\text{Tl}$			$4 \times 10^{-3}$
	$^{201}\text{Tl}$			$3 \times 10^{-3}$
	$^{202}\text{Tl}$			$1 \times 10^{-3}$
	$^{204}\text{Tl}$	50		$1 \times 10^{-3}$
Thulium	$^{170}\text{Tm}$			$5 \times 10^{-4}$
	$^{171}\text{Tm}$			$5 \times 10^{-3}$
Tin	$^{113}\text{Sn}$	10		$9 \times 10^{-4}$
	$^{125}\text{Sn}$			$2 \times 10^{-4}$
Tungsten	$^{181}\text{W}$			$4 \times 10^{-3}$
	$^{185}\text{W}$	10		
	$^{187}\text{W}$			$7 \times 10^{-4}$
Vanadium	$^{48}\text{V}$	1		$3 \times 10^{-4}$
Xenon	$^{131m}\text{Xe}$		$4 \times 10^{-6}$	
	$^{133}\text{Xe}$		$3 \times 10^{-6}$	
	$^{135}\text{Xe}$		$1 \times 10^{-6}$	
Ytterbium	$^{175}\text{Yb}$			$1 \times 10^{-3}$
Yttrium	$^{90}\text{Y}$	1		$2 \times 10^{-4}$
	$^{91m}\text{Y}$			$3 \times 10^{-2}$
	$^{91}\text{Y}$	1		$3 \times 10^{-4}$
	$^{92}\text{Y}$			$6 \times 10^{-4}$
	$^{93}\text{Y}$			$3 \times 10^{-4}$
Zinc	$^{65}\text{Zn}$	10		$1 \times 10^{-3}$
	$^{69m}\text{Zn}$			$7 \times 10^{-4}$
	$^{69}\text{Zn}$			$2 \times 10^{-2}$
Zirconium	$^{95}\text{Zr}$			$6 \times 10^{-4}$
	$^{97}\text{Zr}$			$2 \times 10^{-4}$

<sup>a</sup>Amounts listed are for unsealed sources. Amounts permitted for sealed sources are slightly higher for most radioisotopes.

Table 6 (continued)

Element	Isotopes	Generally Licensed Quantities <sup>a</sup> ( $\mu\text{Ci}$ )	Exempt Concentrations	
			Gas ( $\mu\text{Ci/ml}$ )	Solid ( $\mu\text{Ci/g}$ ) or Liquid ( $\mu\text{Ci/ml}$ )
Beta- or gamma-emitting by-product material not listed above, having a half-life less than 3 y			$1 \times 10^{-10}$	$1 \times 10^{-6}$
Beta- or gamma-emitting material not listed above		1		

<sup>a</sup>Amounts listed are for unsealed sources. Amounts permitted for sealed sources are slightly higher for most radioisotopes.

## METHODS OF PRODUCTION

Radioisotopes are produced in reactors and in accelerators -- particularly cyclotrons. They can be separated from other elements by chemical means and from other isotopes by electromagnetic separators. In both cyclotrons and nuclear reactors, several different nuclear processes produce radioisotopes.

In nuclear reactors, there are essentially two processes: fission and neutron activation. Fission of uranium produces a wide range of radioisotopes of the elements zinc through gadolinium. Figure 13, the well-known "saddle" curve, shows the usual distribution from fission of  $^{235}\text{U}$ . Probably the two best known fission product isotopes are  $^{90}\text{Sr}$  and  $^{137}\text{Cs}$ . Since several isotopes of an element are often produced, isotopic purity is not usually very high. Isotopic purity of fission-produced radioisotopes is dependent on time in two ways: the length of time the uranium was held in the reactor and the elapsed time between removal from the reactor and processing.

The three most common neutron reactions are  $(n,\gamma)$ ,  $(n,p)$ , and  $(n,\alpha)$ . The  $(n,\gamma)$  process takes place when a neutron is captured by a target atom and a gamma photon is emitted; it is the most common neutron reaction. Since no change in the atomic number occurs, the radioisotope is of the same element as the target atom and cannot be separated chemically from the target. The  $(n,\gamma)$  process is a low-energy thermal neutron reaction. An example is  $^{23}\text{Na} + n \rightarrow ^{24}\text{Na} + \gamma$ , also written  $^{23}\text{Na}(n,\gamma)^{24}\text{Na}$ . Other  $(n,\gamma)$  reactions are given in Table 7.

The  $(n,\gamma)$  reaction can be used to generate a high-activity-concentration product if the radioisotope produced (parent) decays to a radioisotope (daughter) that can be separated chemically. Examples of this reaction are given in Table 8.

Neutrons of higher energy may take part in an  $(n,p)$  reaction. In this process a neutron enters a target nucleus with sufficient energy to cause a proton to be simultaneously ejected. As a result the atomic number is reduced by 1, but the atomic weight remains the same; the affected atom is transmuted into a different element and can be separated chemically from the target material. Typical examples of the  $(n,p)$  reaction are given in Table 9.

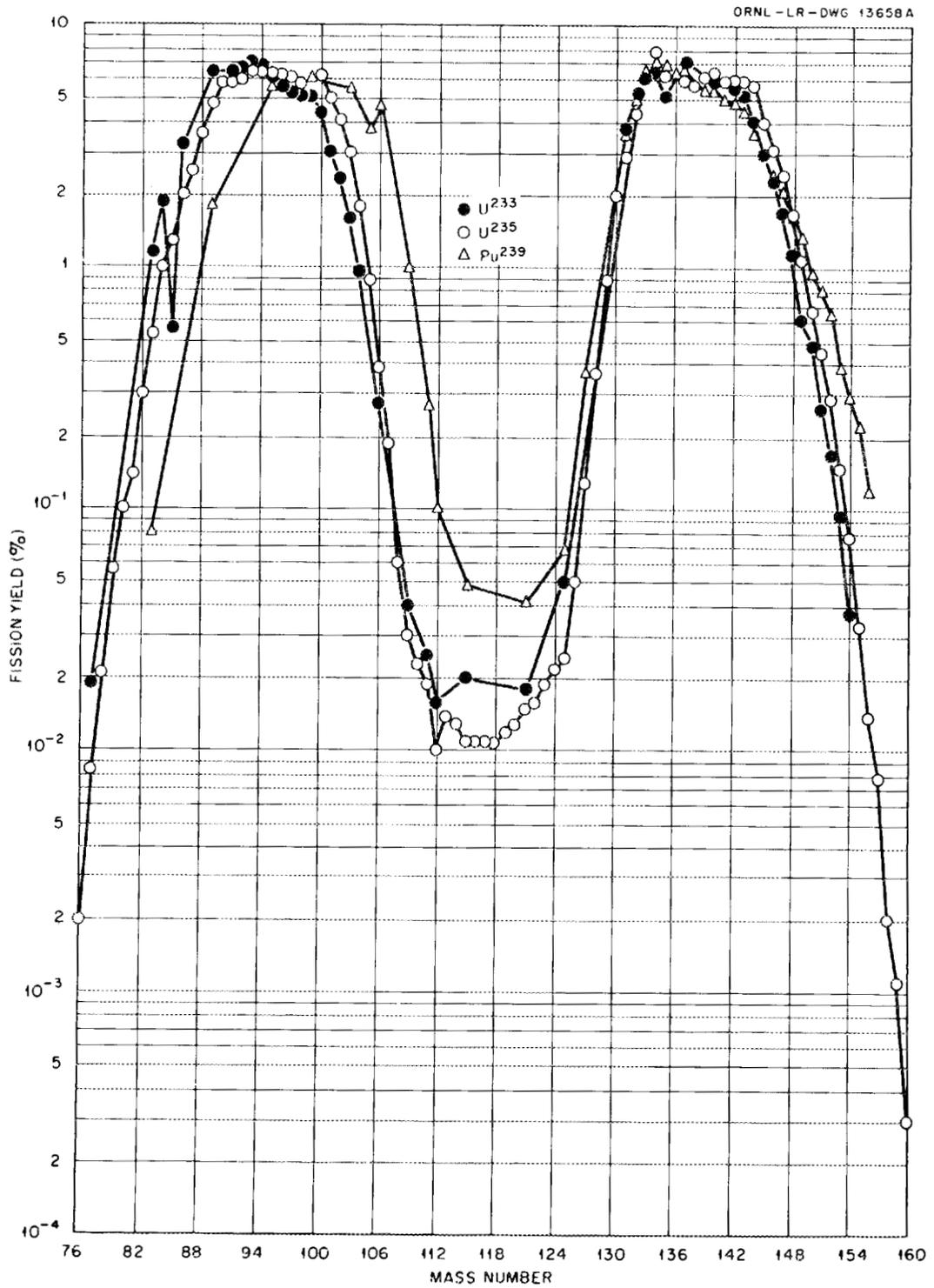


Fig. 13. Distribution of Fission Products from  $^{235}\text{U}$ ,  $^{233}\text{U}$ , and  $^{239}\text{Pu}$ .

Table 7. Isotopes by  $(n,\gamma)$  Reactions

$^{46}\text{Ca}(n,\gamma)^{47}\text{Ca}$
$^{84}\text{Sr}(n,\gamma)^{85}\text{Sr}$
$^{81}\text{Br}(n,\gamma)^{82}\text{Br}$
$^{108}\text{Cd}(n,\gamma)^{109}\text{Cd}$
$^{197}\text{Au}(n,\gamma)^{198}\text{Au}$

Table 8. Isotopes by  $(n,\gamma \xrightarrow{\text{decay}})$  Reactions

$^{76}\text{Ge}(n,\gamma)^{77}\text{Ge} \xrightarrow{\beta^-} ^{77}\text{As}$
$^{110}\text{Pd}(n,\gamma)^{111}\text{Pd} \xrightarrow{\beta^-} ^{111}\text{Ag}$
$^{124}\text{Sn}(n,\gamma)^{125}\text{Sn} \xrightarrow{\beta^-} ^{125}\text{Sb}$
$^{124}\text{Xe}(n,\gamma)^{125}\text{Xe} \xrightarrow{\text{EC}} ^{125}\text{I}$
$^{198}\text{Pt}(n,\gamma)^{199}\text{Pt} \xrightarrow{\beta^-} ^{199}\text{Au}$

Table 9. Isotopes by  $(n,p)$  Reactions

$^{14}\text{N}(n,p)^{14}\text{C}$
$^{32}\text{S}(n,p)^{32}\text{P}$
$^{35}\text{Cl}(n,p)^{35}\text{S}$
$^{58}\text{Ni}(n,p)^{58}\text{Co}$

Table 10. Examples of Typical Cyclotron Reactions

$(p,n)$	$^{55}\text{Mn}(p,n)^{55}\text{Fe}$
$(p,2n)$	$^{96}\text{Mo}(p,2n)^{95}\text{Tc}$
$(p,\alpha)$	$^{25}\text{Mg}(p,\alpha)^{22}\text{Na}$
$(p,pn)$	$^{48}\text{Ca}(p,pn)^{47}\text{Ca}$

The  $(n,\alpha)$  process is also a high-energy reaction. It results in the absorption of a neutron and the ejection of an alpha particle. The atomic number of the target is reduced by 2, and the atomic weight is reduced by 3. Chemical separation is possible, since the target and the radioisotope produced are different elements. An example of the  $(n,\alpha)$  process is  $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$ .

The cyclotron produces radioisotopes by bombarding targets with charged particles, usually protons or deuterons. Typical cyclotron production reactions are shown in Table 10. Since these reactions all involve high-energy "projectiles," there is almost invariably the simultaneous ejection of a neutron or other particle; furthermore, the radioisotopes produced are usually neutron deficient and are transmutation products, so that they may be chemically separated in near theoretical activity concentration. Otherwise, the processing of the target is very similar to that for neutron products.

### Activity Production Calculation

The basic equation used to calculate the activity of a radioisotope produced by exposure of a target in a reactor is

$$A = \frac{Nf\sigma S}{(3.7 \times 10^{10})}$$

where  $A$  is the activity in curies,  $f$  is the neutron flux (neutrons  $\text{cm}^{-2} \text{sec}^{-1}$ ),  $\sigma$  is the activation cross section of the target isotope ( $\text{cm}^2$ ),  $N$  is the number of atoms of the target isotope,  $S$  is the saturation factor (Table 11 and Fig. 14). The number of atoms of the target isotope can be calculated by

$$N = N_0 kW/M$$

where  $N_0$  is Avogadro's number,  $6.02 \times 10^{23}$  atoms per gram atomic weight;  $k$  is the fraction of the atoms of the target element that are atoms of the target isotope (e.g., for production of  $^{204}\text{Tl}$ , the fraction of thallium that is  $^{203}\text{Tl}$ );  $W$  is the weight of the target element in the target in grams (e.g., a  $\text{Tl}_2\text{O}_3$  target weighing 0.60 g contains 0.54 g of thallium);  $M$  is the atomic mass number of the target isotope (e.g., if

$^{203}\text{Tl}$  is irradiated to get  $^{204}\text{Tl}$ , then  $M$  is 203). The saturation factor is  $S = 1 - e^{-\lambda t}$ , where  $t$  is the length of time of irradiation, and  $\lambda$  is  $0.693/T$  where  $T$  is the half-life of the produced radioisotope. The saturation factor is often set at 1 when the length of time of irradiation approaches five or more half-lives. Values of  $S$  are given in Fig. 14 and in Table 11.

**Table 11. Growth of a Radioelement  
(Produced at Constant Rate)**

$S = \text{fraction of saturation value} = 1 - e^{-\lambda t}$

Half-Lives	$S$	Half-Lives	$S$	Half-Lives	$S$
0.01	0.0069	0.98	0.493	1.96	0.743
0.02	0.0138	1.00	0.500	1.98	0.747
0.04	0.0273	1.02	0.507	2.00	0.750
0.06	0.0407	1.04	0.514	2.05	0.759
0.08	0.0539	1.06	0.520	2.10	0.767
0.10	0.0670	1.08	0.527	2.15	0.775
0.12	0.0798	1.10	0.533	2.20	0.782
0.14	0.0925	1.12	0.540	2.25	0.790
0.16	0.105	1.14	0.546	2.30	0.797
0.18	0.117	1.16	0.553	2.35	0.804
0.20	0.129	1.18	0.559	2.40	0.811
0.22	0.141	1.20	0.565	2.45	0.817
0.24	0.153	1.22	0.571	2.50	0.823
0.26	0.165	1.24	0.577	2.55	0.829
0.28	0.176	1.26	0.582	2.60	0.835
0.30	0.188	1.28	0.588	2.65	0.841
0.32	0.199	1.30	0.594	2.70	0.846
0.34	0.210	1.32	0.599	2.75	0.851
0.36	0.221	1.34	0.605	2.80	0.856
0.38	0.232	1.36	0.610	2.85	0.861
0.40	0.242	1.38	0.616	2.90	0.866
0.42	0.253	1.40	0.621	2.95	0.871
0.44	0.263	1.42	0.626	3.00	0.875
0.46	0.273	1.44	0.631	3.10	0.883
0.48	0.283	1.46	0.636	3.20	0.891
0.50	0.293	1.48	0.641	3.30	0.898
0.52	0.303	1.50	0.646	3.40	0.905
0.54	0.312	1.52	0.651	3.50	0.912
0.56	0.322	1.54	0.656	3.60	0.918
0.58	0.331	1.56	0.661	3.70	0.923
0.60	0.340	1.58	0.666	3.80	0.928
0.62	0.349	1.60	0.670	3.90	0.933
0.64	0.358	1.62	0.675	4.00	0.938
0.66	0.367	1.64	0.679	4.25	0.947
0.68	0.376	1.66	0.684	4.50	0.956
0.70	0.384	1.68	0.688	4.75	0.963
0.72	0.393	1.70	0.692	5.00	0.969
0.74	0.401	1.72	0.696	5.25	0.974
0.76	0.410	1.74	0.701	5.50	0.978
0.78	0.418	1.76	0.705	5.75	0.981
0.80	0.426	1.78	0.709	6.00	0.984
0.82	0.434	1.80	0.713	6.50	0.989
0.84	0.441	1.82	0.717	7.00	0.992
0.86	0.449	1.84	0.721	7.50	0.994
0.88	0.457	1.86	0.725	8.00	0.996
0.90	0.464	1.88	0.728	9.00	0.998
0.92	0.471	1.90	0.732	10.00	0.999
0.94	0.479	1.92	0.736		
0.96	0.486	1.94	0.739		

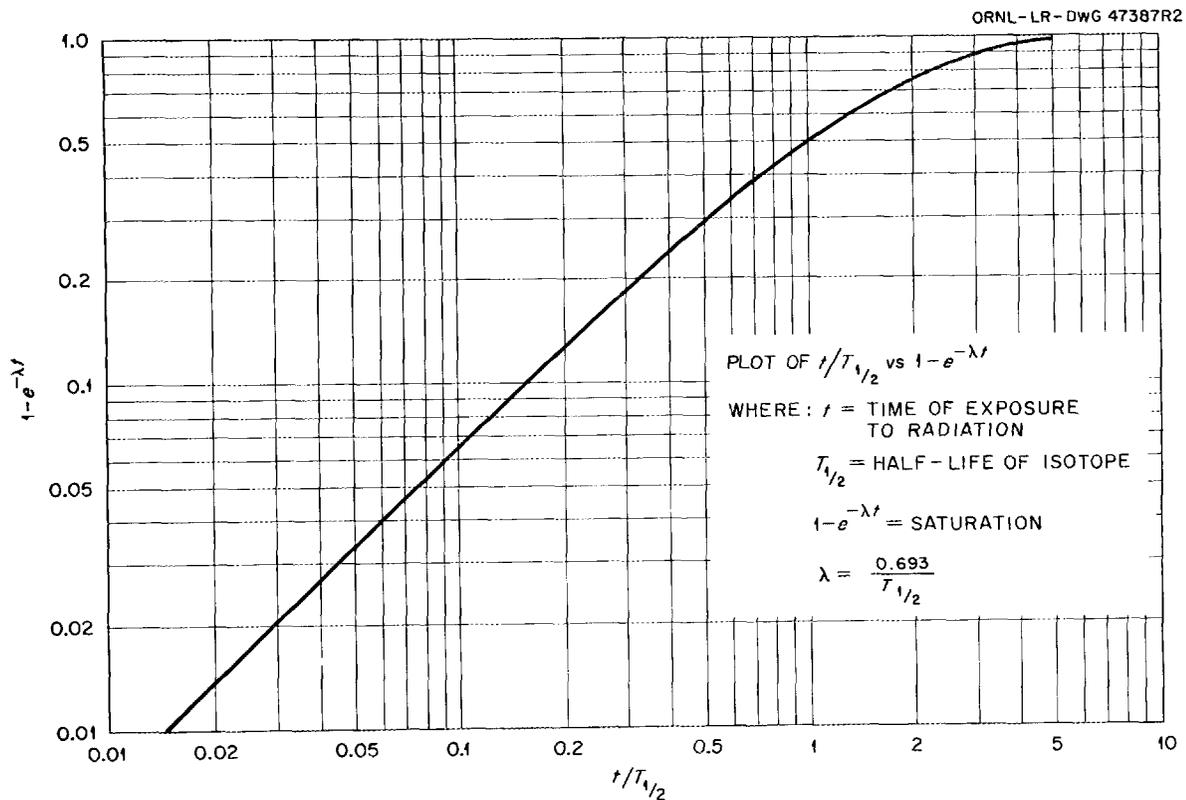


Fig. 14. Growth of a Radioisotope.

To demonstrate the use of these two formulas, let us calculate the activity of a 0.6-g target of  $\text{Na}_2\text{CO}_3$  exposed for seven days in a reactor with a neutron flux of  $5 \times 10^{11}$  neutrons  $\text{cm}^{-2} \text{sec}^{-1}$  to produce  $^{24}\text{Na}$ . First, calculate the value of  $N$ ;  $k = 1$  because stable sodium is mononuclidic,  $M = 23$  from the stable sodium isotope  $^{23}\text{Na}$ , and  $W = 0.26$  (i.e.,  $2\text{Na}/\text{Na}_2\text{CO}_3 = 46/106 = 0.43$ ;  $0.43 \times 0.6 = 0.26$ ). Thus

$$N = \frac{(6.02 \times 10^{23})(1)(0.26)}{23} = 6.8 \times 10^{21}$$

This value is then used to calculate the activity,  $A$ :  $N = 6.8 \times 10^{21}$ ;  $f$  is given as  $5 \times 10^{11}$ ; the cross section for the  $(n, \gamma)$  reaction in  $^{23}\text{Na}$  is 0.6 barn, or  $0.6 \times 10^{-24} \text{cm}^2$ ; and  $S = 1$  because the seven-day irradiation period is longer than five half-lives of  $^{24}\text{Na}$ , which is  $T = 15$  h. Finally, we see that

$$A = \frac{(6.8 \times 10^{21})(5 \times 10^{11})(0.6 \times 10^{-24})(1)}{3.7 \times 10^{10}},$$

$$A = 0.055 \text{ Ci or } 55 \text{ mCi of } ^{24}\text{Na}.$$

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### TYPICAL ASSAY METHODS USED IN RADIOISOTOPE PRODUCTION

The methods for the calibration and routine measurement of common radioisotopes given in this section are typical of the methods generally used commercially. For those used at Oak Ridge National Laboratory, estimates of both the *accuracy* of disintegration-rate determinations and the *precision* of routine measurements are furnished in Table 12. The latter value indicates the reproducibility to be expected among several shipments of a given material. Accuracy refers to the routine measurement of millicuries per milliliter in shipments, rather than to the primary calibration itself (i.e., by coincidence or  $4\pi$  counting). Modes of decay and values for half-lives are included. A radioactive daughter is usually listed with its parent (e.g.,  $^{113}\text{Sn}$ - $^{113}\text{In}$ ) if its half-life is short compared with that of the parent; otherwise it is listed under "Remarks." Also under "Remarks" are listed some radioactive daughters, isotopic impurities, and gamma energies in MeV for single prominent gamma rays that will permit quantitative gamma spectrometry. References 1-3 should be consulted for details of decay schemes, and references 4 and 5 give some generalities on assay methods.

Many radioisotopes are shipped in solution form, and volumetric techniques are used to obtain the sample for activity measurements. When beta activity is to be determined, the sample is dried on a suitable film or plate and mounted so that it can be inserted in a counter. Samples for gamma and x-ray spectrometry are often dried on 1-in. watch glasses, while measurements of total gamma activity are made on liquid samples.

The fundamental method of standardization of beta-gamma-emitting nuclides is  $4\pi$  beta-gamma coincidence counting, employing an instrument in which the beta detector is a  $4\pi$  counter and the gamma detector is a NaI(Tl) scintillation spectrometer, equipped with a differential and integral analyzer circuit.

Table 12. Methods for Assay of Radioisotopes

Isotope	Half-Life	Decay Modes	Assay Instrument <sup>a</sup>		Limit <sup>b</sup> of Error (%)	Precision <sup>c</sup> (%)	Remarks
			Calibration	Routine			
<sup>227</sup> Ac	21.8 y	$\beta^-$	W	LS			Calibrated by $\alpha$ of Th daughter
<sup>26</sup> Al	$7.4 \times 10^5$ y	$\beta^+$ , EC, $\gamma$	$\gamma$ S	$\gamma$ S			Counting of $\gamma^{\pm}$
<sup>241</sup> Am	433 y	$\alpha, \gamma, e^-$	D	W	5	3	
<sup>122</sup> Sb	2.75 d	$\beta^-, EC, \gamma$	PC	IC, SC	10	2	
<sup>124</sup> Sb	60.2 d	$\beta^-, \gamma$	$4\pi$ C	IC, SC	10	2	$\gamma = 1.69$
<sup>125</sup> Sb	2.7 y	$\beta^-, \gamma$	$4\pi$ C	IC, SC	10	2	<sup>125m</sup> Te daughter
<sup>37</sup> Ar	35 d	EC	$\gamma$ S	$\gamma$ S	10	5	Bremsstrahlung distribution integrated, $4 \times 10^{-4}$ Brm/dis
<sup>39</sup> Ar	$\sim 265$ y	$\beta^-$	G <sup>d</sup>	$\gamma$ S			Bremsstrahlung measured
<sup>73</sup> As	80 d	EC, $\gamma, e^-$	X, $\gamma$ S	X, $\gamma$ S	30	10	<sup>74</sup> As by $\gamma$ S
<sup>74</sup> As	17.8 d	EC, $\beta^+, \beta^-, \gamma$	$\gamma$ S	$\gamma$ S	30	5	
<sup>76</sup> As	26.4 h	$\beta^-, \gamma$	$4\pi$	IC, SC	10	2	
<sup>77</sup> As	38.7 h	$\beta^-, \gamma$	$4\pi$	PC	10	5	
<sup>131</sup> Ba	12 d	EC, $\gamma, e^-$	$\gamma$ S	$\gamma$ S	10	5	
<sup>133</sup> Ba	10.7 y	EC, $\gamma, e^-$	IC	IC, $\gamma$ S	10	2	
<sup>140</sup> Ba	12.8 d	$\beta^-, \gamma$	$4\pi$ C	IC, PC	10	5	<sup>140</sup> La daughter
<sup>7</sup> Be	53 d	EC, $\gamma$	IC	IC, SC	5	2	
<sup>10</sup> Be	$2.7 \times 10^6$ y	$\beta^-$	PC	PC			<sup>90</sup> Sr standard
<sup>206</sup> Bi	6.24 d	EC, $\gamma, e^-$	X- $\gamma$ C	$\gamma$ S			$\gamma = 1.72$
<sup>207</sup> Bi	30 y	EC, $\gamma$	X- $\gamma$ C	$\gamma$ S			$\gamma = 1.06$
<sup>210</sup> Bi	5.0 d	$\beta^-$	PC	PC	10	5	<sup>210</sup> Po daughter
<sup>77</sup> Br	56 h	EC, $\gamma, e^-$	X- $\gamma$ C	$\gamma$ S			$\gamma = 0.52$
<sup>82</sup> Br	35.4 h	$\beta^-, \gamma$	$4\pi$ C	IC, SC	5	2	
<sup>109</sup> Cd	1.24 y	EC, $\gamma, e^-$	$\gamma$ S	$\gamma$ S	20	5	<sup>109m</sup> Ag daughter; x-ray measurement
<sup>113m</sup> Cd	14 y	$\beta^-$	PC	PC			<sup>90</sup> Sr standard
<sup>115m</sup> Cd	43 d	$\beta^-, \gamma$	$4\pi$	PC	10	3	
<sup>115</sup> Cd	55 h	$\beta^-, \gamma$	$\gamma$ S	PC	20	5	$\gamma$ of <sup>115m</sup> In daughter measured
<sup>45</sup> Ca	164 d	$\beta^-$	$4\pi$	LS	10	3	
<sup>47</sup> Ca	4.53 d	$\beta^-, \gamma$	$4\pi$ C	$\gamma$ S	10	2	<sup>47</sup> Sc daughter
<sup>14</sup> C	$5.73 \times 10^3$ y	$\beta^-$	LS	LS	5	5	
<sup>139</sup> Ce	138 d	EC, $\gamma, e^-$	X- $\gamma$ C	$\gamma$ S			
<sup>141</sup> Ce	32.5 d	$\beta^-, \gamma$	$4\pi$ C	$\gamma$ S	10	5	Correction for <sup>144</sup> Ce (see below)
<sup>143</sup> Ce	33 h	$\beta^-, \gamma, e^-$	$4\pi$ C	$\gamma$ S			$\gamma = 0.29$
<sup>144</sup> Ce	284 d	$\beta^-, \gamma, e^-$	PC	PC	10	4	<sup>144</sup> Pr daughter
<sup>131</sup> Cs	9.7 d	EC	$\gamma$ S	$\gamma$ S	10	5	X rays counted
<sup>132</sup> Cs	6.5 d	EC, $\beta^-, \gamma$	X- $\gamma$ C	$\gamma$ S			
<sup>134</sup> Cs	2.07 y	$\beta^-, \gamma$	$4\pi$ C	IC	10	2	
<sup>137</sup> Cs	30 y	$\beta^-$	IC	IC, SC	5	2	<sup>137m</sup> Ba daughter
<sup>36</sup> Cl	$3.0 \times 10^5$ y	$\beta^-, EC$	LS	LS	5	3	
<sup>38</sup> Cl	37.3 m	$\beta^-, \gamma$	$\gamma$ S, IC	$\gamma$ S, IC			$\gamma = 2.17$
<sup>51</sup> Cr	27.8 d	EC, $\gamma$	X- $\gamma$ C	IC, SC	10	5	
<sup>56</sup> Co	77.3 d	EC, $\beta^+, \gamma$	$\gamma$ S	$\gamma$ S	5	3	
<sup>57</sup> Co	270 d	EC, $\gamma, e^-$	$\gamma$ S	$\gamma$ S	10	5	
<sup>58</sup> Co	71 d	$\beta^+, EC, \gamma$	$\gamma$ S	IC, SC	10	2	
<sup>60</sup> Co	5.26 y	$\beta^-, \gamma$	$4\pi$ C	IC, SC	3	2	

Table 12 (continued)

Isotope	Half-Life	Decay Modes	Assay Instrument <sup>a</sup>		Limit <sup>b</sup> of Error (%)	Precision <sup>c</sup> (%)	Remarks
			Calibration	Routine			
<sup>64</sup> Cu	12.7 h	$\beta^-$ , $\beta^+$ , EC, $\gamma$	IC	IC, SC	20	2	
<sup>67</sup> Cu	61.7 h	$\beta^-$ , $\gamma$	$\gamma$ S	$\gamma$ S	10	5	
<sup>242</sup> Cm	163 d	$\alpha$ , $\gamma$ , $e^-$	D	W	5	3	
<sup>244</sup> Cm	18.1 y	$\alpha$ , $\gamma$ , $e^-$	D	W	5	3	
<sup>159</sup> Dy	144 d	EC, $\gamma$ , $e^-$	$\gamma$ S	$\gamma$ S			X rays counted
<sup>165</sup> Dy	2.35 h	$\beta^-$ , $\gamma$	PC	PC			<sup>210</sup> Bi standard
<sup>169</sup> Er	9.3 d	$\beta^-$ , $\gamma$ , $e^-$	LS	LS			<sup>60</sup> Co standard
<sup>171</sup> Er	7.5 h	$\beta^-$ , $\gamma$ , $e^-$	$\gamma$ S	$\gamma$ S			$\gamma = 0.30-0.31$
<sup>150</sup> Eu	12.8 h	$\beta^-$ , EC, $\gamma$ , $e^-$	PC	PC			
<sup>152m</sup> Eu	9.3 h	$\beta^-$ , EC, $\gamma$ , $e^-$	$\gamma$ S, IC	$\gamma$ S, IC			$\gamma = 0.96$
<sup>152</sup> Eu- <sup>154</sup> Eu	12.7 y; 16 y	$\beta^-$ , EC, $\gamma$ , $e^-$ ; $\beta^-$ , $\gamma$ , $e^-$	$\gamma$ S	SC, $\gamma$ S	30	5	
<sup>155</sup> Eu	1.81 y	$\beta^-$ , $\gamma$ , $e^-$	4 $\pi$ C	$\gamma$ S			
<sup>18</sup> F	110 m	$\beta^+$ , EC	$\gamma$ S, IC	$\gamma$ S, IC			$\gamma^\pm$
<sup>148</sup> Gd	88 y	$\alpha$	W	W			
<sup>153</sup> Gd	240 d	EC, $\gamma$ , $e^-$	X- $\gamma$ C	$\gamma$ S			$\gamma = 0.10$
<sup>159</sup> Gd	18 h	$\beta^-$ , $\gamma$ , $e^-$	$\gamma$ S	$\gamma$ S			$\gamma = 0.36$
<sup>66</sup> Ga	9.5 h	$\beta^+$ , EC, $\gamma$	$\gamma$ S	$\gamma$ S			$\gamma^\pm$
<sup>67</sup> Ga	78 h	EC, $\gamma$ , $e^-$	X- $\gamma$ C	$\gamma$ S			$\gamma = 0.30$
<sup>72</sup> Ga	14.1 h	$\beta^-$ , $\gamma$	4 $\pi$	IC, SC	10	2	
<sup>68</sup> Ge	280 d	EC	$\gamma$ S	$\gamma$ S			<sup>68</sup> Ga daughter; $\gamma^\pm$
<sup>71</sup> Ge	11.4 d	EC	X	X	10	5	
<sup>77</sup> Ge	11.3 h	$\beta^-$ , $\gamma$	$\gamma$ S	$\gamma$ S			$\gamma = 0.56 + 0.63$
<sup>195</sup> Au	183 d	EC, $\gamma$ , $e^-$	X- $\gamma$ C	$\gamma$ S			X rays counted
<sup>198</sup> Au	2.70 d	$\beta^-$ , $\gamma$	4 $\pi$ C	IC, SC	3	2	
<sup>199</sup> Au	3.15 d	$\beta^-$ , $\gamma$ , $e^-$	4 $\pi$ C	IC, $\gamma$ S	10	5	<sup>198</sup> Au by $\gamma$ S
<sup>175</sup> Hf	70 d	EC, $\gamma$ , $e^-$	X- $\gamma$ C	$\gamma$ S			
<sup>181</sup> Hf	42.5 d	$\beta^-$ , $\gamma$	$\gamma$ S	$\gamma$ S	10	5	0.48-MeV $\gamma$ measured; <sup>175</sup> Hf by $\gamma$ S
<sup>166m</sup> Ho	$1.2 \times 10^3$ y	$\beta^-$ , $\gamma$ , $e^-$	$\gamma$ S	$\gamma$ S			$\gamma = 0.81 + 0.83$
<sup>166</sup> Ho	27.0 h	$\beta^-$ , $\gamma$ , $e^-$	4 $\pi$	PC			
<sup>3</sup> H	12.3 y	$\beta^-$	LS	LS	5	5	
<sup>111</sup> In	67.4 h	EC, $\gamma$ , $e^-$	$\gamma$ S	$\gamma$ S			$\gamma = 0.25$
<sup>114m-114</sup> In	50 d; 72 s	IT, EC, $e^-$ ; $\beta^-$ , EC	4 $\pi$	PC	10	4	$\beta$ disintegration rate measured
<sup>116m</sup> In	54 m	$\beta^-$ , $\gamma$	$\gamma$ S	Various			$\gamma = 1.29$
<sup>123</sup> I	13 h	EC, $\gamma$ , $e^-$	$\gamma$ S	$\gamma$ S			
<sup>124</sup> I	4.2 d	EC, $\beta^+$ , $\gamma$	$\gamma$ S	$\gamma$ S			$\gamma = 1.69$
<sup>125</sup> I	60 d	EC, $\gamma$ , $e^-$	$\gamma$ S	$\gamma$ S	20	5	Sum-coincidence calibrated
<sup>126</sup> I	13 d	EC, $\beta^-$ , $\gamma$	$\gamma$ S	$\gamma$ S			<sup>113</sup> Sn standard
<sup>129</sup> I	$1.6 \times 10^7$ y	$\beta^-$ , $\gamma$ , $e^-$	CC	$\gamma$ S	10	5	
<sup>130</sup> I	12.3 h	$\beta^-$ , $\gamma$	IC	SC, IC	10	2	
<sup>131</sup> I	8.06 d	$\beta^-$ , $\gamma$ , $e^-$	4 $\pi$ C	IC, SC	3	2	
<sup>132</sup> I	2.3 h	$\beta^-$ , $\gamma$	$\gamma$ S	$\gamma$ S, IC			$\gamma = 0.65 + 0.67$
<sup>133</sup> I	20.9 h	$\beta^-$ , $\gamma$	$\gamma$ S	$\gamma$ S			$\gamma = 0.53$
<sup>192</sup> Ir	74 d	$\beta^-$ , EC, $\gamma$	4 $\pi$	IC, SC	20	2	$\beta$ disintegration rate measured

Table 12 (continued)

Isotope	Half-Life	Decay Modes	Assay Instrument <sup>a</sup>		Limit <sup>b</sup> of Error (%)	Precision <sup>c</sup> (%)	Remarks
			Calibration	Routine			
<sup>194</sup> Ir	19.4 h	$\beta^-$ , $\gamma$	4 $\pi$	PC	10	5	
<sup>52</sup> Fe	8.3 h	$\beta^+$ , EC, $\gamma$	$\gamma$ S	$\gamma$ S			$\gamma = 0.17$
<sup>55</sup> Fe	2.7 y	EC	X	X	30	10	<sup>59</sup> Fe content by IC, $\gamma$ S
<sup>59</sup> Fe	44.6 d	$\beta^-$ , $\gamma$	4 $\pi$ C	IC, SC	5	2	<sup>55</sup> Fe content by X
<sup>79</sup> Kr	35 h	$\beta^+$ , EC, $\gamma$	$\gamma$ S	$\gamma$ S	10	5	
<sup>85m</sup> Kr	4.4 h	$\beta^-$ , IT, $\gamma$ , $e^-$	$\gamma$ S	$\gamma$ S			$\gamma = 0.15$
<sup>85</sup> Kr	10.7 y	$\beta^-$ , $\gamma$	PC	$\gamma$ S	10	3	
<sup>140</sup> La	40.2 h	$\beta^-$ , $\gamma$	4 $\pi$ C	IC, SC	5	2	
<sup>210</sup> Pb	21.3 y	$\beta^-$ , $\gamma$ , $e^-$	PC	LS			<sup>210</sup> Bi calibration
<sup>173</sup> Lu	1.4 y	EC, $\gamma$ , $e^-$	X- $\gamma$ C	$\gamma$ S			$\gamma = 0.27$
<sup>177</sup> Lu	6.7 d	$\beta^-$ , $\gamma$ , $e^-$	4 $\pi$ C	$\gamma$ S			$\gamma = 0.21$
<sup>28</sup> Mg	21.1 h	$\beta^-$ , $\gamma$	$\gamma$ S	$\gamma$ S, IC			<sup>28</sup> Al daughter; $\gamma = 1.78$
<sup>52</sup> Mn	5.7 d	EC, $\beta^+$ , $\gamma$	$\gamma$ S	$\gamma$ S			$\gamma = 1.43$
<sup>54</sup> Mn	313 d	EC, $\gamma$	X- $\gamma$ C	IC, SC	3	2	
<sup>56</sup> Mn	2.58 h	$\beta^-$ , $\gamma$	$\gamma$ S, IC	$\gamma$ S, IC			
<sup>197</sup> Hg	64 h	EC, $\gamma$ , $e^-$	$\gamma$ S	$\gamma$ S	10	5	K x rays + 0.077 $\gamma$ assumed 100%
<sup>203</sup> Hg	46.5 d	$\beta^-$ , $\gamma$	4 $\pi$ C	IC, SC	5	2	
<sup>99</sup> Mo	66.3 h	$\beta^-$ , $\gamma$	4 $\pi$ C	PC	10	2	<sup>99m</sup> Tc daughter
<sup>147</sup> Nd	11.1 d	$\beta^-$ , $\gamma$ , $e^-$	4 $\pi$ C	IC, SC	10	3	<sup>147</sup> Pm daughter
<sup>149</sup> Nd	1.8 h	$\beta^-$ , $\gamma$ , $e^-$	$\gamma$ S	$\gamma$ S			$\gamma = 0.27$
<sup>237</sup> Np	$2.14 \times 10^6$ y	$\alpha$ , $\gamma$ , $e^-$	W	W			
<sup>59</sup> Ni	$8 \times 10^4$ y	EC	X	X	30	10	
<sup>63</sup> Ni	92 y	$\beta^-$	PC	LS	30	10	
<sup>65</sup> Ni	2.56 h	$\beta^-$ , $\gamma$	$\gamma$ S	$\gamma$ S			$\gamma = 1.48$
<sup>66</sup> Ni- <sup>66</sup> Cu	55 h; 5 m	$\beta^-$ ; $\beta^-$ , $\gamma$	$\gamma$ S	$\gamma$ S			$\gamma = 1.04$
<sup>94</sup> Nb	$2.0 \times 10^4$ y	$\beta^-$ , $\gamma$	$\gamma$ S, IC	$\gamma$ S, IC	3	2	
<sup>95</sup> Nb	35 d	$\beta^-$ , $\gamma$	4 $\pi$ C	IC, SC	5	2	
<sup>185</sup> Os	94 d	EC, $\gamma$ , $e^-$	X- $\gamma$ C	$\gamma$ S			$\gamma = 0.65$
<sup>191m</sup> Os	13 h	IT, $e^-$	$\gamma$ S	$\gamma$ S			By <sup>191</sup> Os daughter
<sup>191</sup> Os	15 d	$\beta^-$ , $\gamma$ , $e^-$	$\gamma$ S	$\gamma$ S	20	5	
<sup>193</sup> Os	32 h	$\beta^-$ , $\gamma$ , $e^-$	4 $\pi$ C	PC			
<sup>103</sup> Pd	17 d	EC, $e^-$	X	X			Corrected for <sup>103m</sup> Rh x ray
<sup>109</sup> Pd	13.6 h	$\beta^-$ , IT, $e^-$	PC	PC	10	5	<sup>109m</sup> Ag daughter; <sup>109</sup> Cd standard
<sup>32</sup> P	14.3 d	$\beta^-$	4 $\pi$	PC	3	2	
<sup>33</sup> P	25 d	$\beta^-$	LS	LS	10	3	<sup>45</sup> Ca standard
<sup>193m</sup> Pt	4.3 d	IT, $e^-$	$\gamma$ S	$\gamma$ S			K x disintegration rate reported
<sup>197</sup> Pt	20 h	$\beta^-$ , $\gamma$ , $e^-$	$\gamma$ S	$\gamma$ S			
<sup>237</sup> Pu	45.6 d	EC, $\gamma$ , $e^-$	$\gamma$ S	$\gamma$ S			K x disintegration rate reported
<sup>238</sup> Pu	87.6 y	$\alpha$ , $e^-$	D	W	5	3	
<sup>239</sup> Pu	$2.44 \times 10^4$ y	$\alpha$ , $e^-$	D	W	5	3	
<sup>208</sup> Po	2.9 y	$\alpha$	D	W	5	3	
<sup>210</sup> Po	138.4 d	$\alpha$	D	W	5	3	

Table 12 (continued)

Isotope	Half-Life	Decay Modes	Assay Instrument <sup>a</sup>		Limit <sup>b</sup> of Error (%)	Precision <sup>c</sup> (%)	Remarks
			Calibration	Routine			
<sup>40</sup> K	1.28 × 10 <sup>9</sup> y	β <sup>-</sup> , EC, γ	γS	γS			Chemical K standard
<sup>42</sup> K	12.4 h	β <sup>-</sup> , γ	4πC	IC, SC	5	3	
<sup>43</sup> K	22 h	β <sup>-</sup> , γ	γS	γS	5	3	γ = 0.59 + 0.61
<sup>142</sup> Pr	19.2 h	β <sup>-</sup> , γ	4πC	IC, PC	10	5	
<sup>143</sup> Pr	13.6 d	β <sup>-</sup>	4π	PC	10	4	
<sup>145</sup> Pm	18 y	EC, γ, e <sup>-</sup>	γS	γS			K x disintegration rate reported
<sup>146</sup> Pm	5.5 y	EC, β <sup>-</sup> , γ	γS	γS			γ = 0.74 + 0.75
<sup>147</sup> Pm	2.62 y	β <sup>-</sup>	4π	LS	5	3	
<sup>149</sup> Pm	53 h	β <sup>-</sup> , γ	4π	PC			
<sup>151</sup> Pm	28 h	β <sup>-</sup> , γ, e <sup>-</sup>	γS	γS			γ = 0.34
<sup>231</sup> Pa	3.4 × 10 <sup>4</sup> y	α, γ, e <sup>-</sup>	D	W			
<sup>233</sup> Pa	27.0 d	β <sup>-</sup> , γ, e <sup>-</sup>	γS	γS	10	3	Calibration by α of <sup>237</sup> Np parent
<sup>234</sup> Pa	6.7 h	β <sup>-</sup> , γ, e <sup>-</sup>	γS	γS			γ = 0.90
<sup>224</sup> Ra	87.4 h	α, γ	γS	γS			<sup>228</sup> Th standard (parent)
<sup>226</sup> Ra	1600 y	α, γ	Various	Various			
<sup>228</sup> Ra	5.7 y	β <sup>-</sup>	γS	γS			0.91–0.96-MeV γ from <sup>228</sup> Ac daughter
<sup>222</sup> Rn	3.82 d	α	G	G			
<sup>183</sup> Re	70 d	EC, γ, e <sup>-</sup>	X-γC	γS			γ = 0.16
<sup>186</sup> Re	90 h	β <sup>-</sup> , EC, γ	4πC	γS	20	5	
<sup>188</sup> Re	17 h	β <sup>-</sup> , γ, e <sup>-</sup>	PC	γS			
<sup>102</sup> Rh	206 d	EC, β <sup>-</sup> , β <sup>+</sup> , γ	γS	γS			γ = 0.48 + γ <sup>±</sup>
<sup>103m</sup> Rh	57 m	IT, e <sup>-</sup>	γS	γS	30	5	X rays counted
<sup>105</sup> Rh	36 h	β <sup>-</sup> , γ	γS	γS			
<sup>83</sup> Rb	83 d	EC, γ, e <sup>-</sup>	γS	γS			
<sup>84</sup> Rb	33 d	β <sup>+</sup> , β <sup>-</sup> , EC, γ	γS	γS	5	3	γ = 0.88
<sup>86</sup> Rb	18.7 d	β <sup>-</sup> , γ	4πC	γS	10	3	
<sup>97</sup> Ru	69.6 h	EC, γ, e <sup>-</sup>	X	γS	30	5	γ = 0.22
<sup>103</sup> Ru	39.7 d	β <sup>-</sup> , γ	4πC	γS	10	5	γ = 0.51
<sup>106</sup> Ru- <sup>106</sup> Rh	1.01 y; 30 s	β <sup>-</sup> ; β <sup>-</sup> , γ	4πC	PC	5	3	<sup>103</sup> Ru by γS; <sup>106</sup> Rh γ = 0.62
<sup>151</sup> Sm	~90 y	β <sup>-</sup> , e <sup>-</sup>	LS	LS			<sup>63</sup> Ni standard
<sup>153</sup> Sm	46.8 h	β <sup>-</sup> , γ	4πC	PC	10	5	
<sup>44</sup> Sc	3.9 h	β <sup>+</sup> , EC, γ	γS	γS			γ = 1.16
<sup>46</sup> Sc	84 d	β <sup>-</sup> , γ	4πC	IC, SC	3	2	
<sup>47</sup> Sc	3.4 d	β <sup>-</sup> , γ	4πC	γS			
<sup>75</sup> Se	120 d	EC, γ, e <sup>-</sup>	γS	γS, IC	30	5	
<sup>31</sup> Si	2.62 h	β <sup>-</sup>	PC	PC			<sup>89</sup> Sr standard
<sup>105</sup> Ag	40 d	EC, γ, e <sup>-</sup>	γS	γS			γ = 0.28–0.34
<sup>110m-110</sup> Ag	253 d; 24 s	β <sup>-</sup> , γ, IT; β <sup>-</sup> , γ	4πC	IC, SC	10	2	
<sup>111</sup> Ag	7.5 d	β <sup>-</sup> , γ	γS	IC, PC	10	5	
<sup>22</sup> Na	2.60 y	β <sup>+</sup> , EC, γ	4πC	IC, SC	5	2	
<sup>24</sup> Na	15.0 h	β <sup>-</sup> , γ	4πC	IC, SC	3	2	
<sup>85</sup> Sr	65 d	EC, γ	IC	IC, SC	10	2	<sup>85m</sup> Rb, 0.9 μs = T <sub>1/2</sub>
<sup>87m</sup> Sr	2.8 h	IT, e <sup>-</sup>	γS	γS			<sup>113</sup> Sn standard

Table 12 (continued)

Isotope	Half-Life	Decay Modes	Assay Instrument <sup>a</sup>		Limit <sup>b</sup> of Error (%)	Precision <sup>c</sup> (%)	Remarks
			Calibration	Routine			
<sup>89</sup> Sr	51 d	$\beta^-$	4 $\pi$	PC	5	3	<sup>90</sup> Sr content by Al absorption data on separated Sr
<sup>90</sup> Sr	28.5 y	$\beta^{--}$	4 $\pi$	PC	10	5	<sup>90</sup> Y daughter; <sup>89</sup> Sr content by Al absorption
<sup>35</sup> S	88 d	$\beta^-$	4 $\pi$	LS	10	3	
<sup>179</sup> Ta	~1.6 y	EC	$\gamma$ S	$\gamma$ S			X rays counted
<sup>182</sup> Ta	115 d	$\beta^-, \gamma, e^-$	4 $\pi$	IC	10	3	
<sup>97</sup> Tc	$2.6 \times 10^6$ y	EC	X	X			
<sup>99</sup> Tc	$2.1 \times 10^5$ y	$\beta^-$	4 $\pi^e$	LS	5	3	
<sup>121m-121</sup> Te	154 d; 17 d	IT, EC, $\gamma, e^-$ ; EC, $\gamma$	$\gamma$ S	$\gamma$ S			$\gamma = 0.21(^{121m}\text{Te})$ ; $\gamma = 0.57(^{121}\text{Te})$
<sup>123m</sup> Te	120 d	IT, $\gamma, e^-$	$\gamma$ S	$\gamma$ S			
<sup>125m</sup> Te	58 d	IT, $e^-$	$\gamma$ S	$\gamma$ S	30	5	
<sup>127m-127</sup> Te	109 d; 9.3 h	IT, $e^-, \beta^-; \beta^-$	PC	PC			
<sup>129m-129</sup> Te	34 d; 69 m	IT, $\beta^-, \gamma, e^-$ ; $\beta^-, \gamma, e^-$	$\gamma$ S	$\gamma$ S			$\gamma = 0.69$
<sup>132</sup> Te	78 h	$\beta^-, \gamma, e^-$	$\gamma$ S	$\gamma$ S			Can calibrate with <sup>132</sup> I daughter
<sup>160</sup> Tb	72.4 d	$\beta^-, \gamma, e^-$	4 $\pi$ C	$\gamma$ S			
<sup>161</sup> Tb	6.9 d	$\beta^-, \gamma, e^-$	4 $\pi$ C	$\gamma$ S			X rays + $\gamma = 0.049$
<sup>204</sup> Tl	3.8 y	$\beta^-, \text{EC}$	4 $\pi$	PC	10	2	$\beta$ disintegration rate measured $\gamma = 2.6(^{208}\text{Tl})$
<sup>228</sup> Th	1.91 y	$\alpha, e^-$	D, $\gamma$ S	W, $\gamma$ S			
<sup>230</sup> Th	$8 \times 10^4$ y	$\alpha, e^-$	D	W			
<sup>232</sup> Th	$1.39 \times 10^{10}$ y	$\alpha, e^-$	$\gamma$ S	$\gamma$ S			Chemical Th standard
<sup>234</sup> Th	24 d	$\beta^-, \gamma, e^-$	PC	PC			<sup>234m</sup> Pa daughter; $\beta$ counted
<sup>170</sup> Tm	129 d	$\beta^-, e^-, \gamma$	4 $\pi$ C	PC	10	3	
<sup>171</sup> Tm	700 d	$\beta^-, \gamma, e^-$	LS	LS			
<sup>113</sup> Sn	115 d	EC, $\gamma$	IC	IC, $\gamma$ S	10	2	<sup>113m</sup> In daughter
<sup>119m</sup> Sn	250 d	IT, $\gamma, e^-$	$\gamma$ S	$\gamma$ S			Assay = $\gamma + Kx$
<sup>121</sup> Sn	27 h	$\beta^-$	PC	PC			
<sup>44</sup> Ti	47 y	EC, $\gamma, e^-$	$\gamma$ S	$\gamma$ S			$\gamma = 0.07$ ; calibration by <sup>44</sup> Sc daughter
<sup>181</sup> W	135 d	EC, $e^-$	$\gamma$ S	$\gamma$ S			X rays counted
<sup>185</sup> W	75 d	$\beta^-$	PC	PC	10	3	<sup>181</sup> W by $\gamma$ S
<sup>187</sup> W	24 h	$\beta^-, e^-, \gamma$	4 $\pi$	IC, SC	10	3	
<sup>188</sup> W	69 d	$\beta^-$	PC	PC			Calibration by <sup>188</sup> Re daughter
<sup>232</sup> U	71.7 y	$\alpha, e^-$	D	W	5	3	
<sup>233</sup> U	$1.62 \times 10^5$ y	$\alpha, e^-$	D	W	5	3	
<sup>235</sup> U	$7.13 \times 10^8$ y	$\alpha, \gamma, e^-$	$\gamma$ S	$\gamma$ S			
<sup>238</sup> U	$4.51 \times 10^9$ y	$\alpha, e^-$	W	W			Chemical U standard
<sup>48</sup> V	16.1 d	$\beta^+, \text{EC}, \gamma$	4 $\pi$ C	$\gamma$ S			$\gamma = 1.31$
<sup>49</sup> V	330 d	EC	X	X			
<sup>129m</sup> Xe	8 d	IT, $e^-$	$\gamma$ S	$\gamma$ S			$\gamma = 0.20$
<sup>131m</sup> Xe	12 d	IT, $e^-$	$\gamma$ S	$\gamma$ S	10	5	

Table 12 (continued)

Isotope	Half-Life	Decay Modes	Assay Instrument <sup>a</sup>		Limit <sup>b</sup> of Error (%)	Precision <sup>c</sup> (%)	Remarks
			Calibration	Routine			
<sup>133</sup> Xe	5.3 d	$\beta^-$ , $\gamma$	$\gamma$ S	$\gamma$ S	10	3	
<sup>169</sup> Yb	31 d	EC, $\gamma$ , $e^-$	X- $\gamma$ C	$\gamma$ S			$\gamma = 0.18-0.20$
<sup>175</sup> Yb	4.2 d	$\beta^-$ , $\gamma$ , $e^-$	$\gamma$ S	$\gamma$ S			
<sup>87</sup> Y	80 h	EC, $\gamma$	$\gamma$ S	$\gamma$ S			<sup>113</sup> Sn standard
<sup>88</sup> Y	107 d	EC, $\gamma$	$\gamma$ S	$\gamma$ S	3	2	
<sup>90</sup> Y	64.0 h	$\beta^-$	4 $\pi$	PC	5	3	
<sup>91</sup> Y	59 d	$\beta^-$ , $\gamma$	4 $\pi$	PC	5	3	
<sup>65</sup> Zn	244 d	$\beta^+$ , EC, $\gamma$	X- $\gamma$ C	IC, SC	5	2	
<sup>69m-69</sup> Zn	14 h; 55 m	IT, $e^-$ ; $\beta^-$	$\gamma$ S	$\gamma$ S	5	3	
<sup>95</sup> Zr	65 d	$\beta^-$ , $\gamma$	4 $\pi$ C	SC	5	5	<sup>95</sup> Nb daughter; separation made
<sup>97</sup> Zr- <sup>97m</sup> Nb	17 h; 1.0 m	$\beta^-$ ; $\gamma$	$\gamma$ S	$\gamma$ S			$\gamma = 0.75$

<sup>a</sup>IC = ionization chamber; SC = well-type scintillation counter; 4 $\pi$  = 4 $\pi$  counter; 4 $\pi$ C = 4 $\pi$   $\beta$ - $\gamma$  coincidence counter; X = x-ray spectrometer, proportional or semiconductor; X- $\gamma$ C = x-ray-gamma coincidence counter;  $\gamma$ S = gamma spectrometer; CC = coincidence counter (external sample); PC = end-window proportional counter; LS = liquid scintillation counter; D = defined-geometry counter; W = windowless proportional counter; G = gas counter.

<sup>b</sup>Estimated limit of error in disintegration-rate concentration of routine shipment, excluding decay-scheme errors.

<sup>c</sup>Estimated precision of measurement (95% C.L.); indicates reproducibility.

<sup>d</sup>Determined by mass spectrometry.

<sup>e</sup>Actually determined by a polarographic method.

General coincidence counting is familiar, but 4 $\pi$  beta-gamma coincidence counting is more accurate when refined in the following way: The 4 $\pi$  counter containing the active sample deposited on a thin conducting film is placed next to the scintillation detector. The pulse-height selector of the scintillation spectrometer is set to accept only pulses from a particular gamma ray, usually the photoelectron peak resulting from the most energetic gamma ray present.

Beta emitters with little or no gammas are usually measured by 4 $\pi$  beta counting,<sup>6</sup> calibrated proportional counters,<sup>7</sup> or liquid scintillation counters.<sup>8</sup> Low-energy beta radiation is efficiently measured by liquid scintillation counters with the active sample incorporated in a solution containing a scintillation compound and counted in a vial placed between two photomultiplier tubes.

Calibrated high-pressure ionization chambers or NaI(Tl) gamma-ray spectrometers can be used to determine absolute gamma disintegration rates. Branchings of all gammas must be known for ionization chamber measurements. For NaI(Tl) spectrometry, the area must be integrated under a single photopeak from a known-abundance gamma ray, and the rate is then determined by calculation. The latter technique is especially useful when an independent absolute standardization is impractical, for example, when the nuclide of interest is in a mixture or is short-lived. Useful standards of annihilation radiation, generally applicable to measurement of positron emitters, are <sup>22</sup>Na and <sup>68</sup>Ge-<sup>68</sup>Ga.

X rays, produced by electron capture or conversion electron processes, are measured with an x-ray proportional-counter spectrometer<sup>9</sup> filled with argon or krypton. This instrument is calibrated with sources whose disintegration rates can be determined by other methods.

Instruments used for routine assay are ionization chambers, well-type scintillation counters, G-M counters, proportional counters, liquid scintillation counters, and scintillation spectrometers with sodium iodide detectors for gamma and anthracene for beta activity. The NaI(Tl) spectrometer and the Ge(Li)

solid-state detector are also useful for checking gamma purity. These instruments are calibrated with samples standardized by one of the absolute techniques described.

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### AVAILABILITY OF STANDARDS

Currently available radioactivity standards are listed in Table 13. Understandably, the short-lived nuclides are available only at intervals. In addition to the listed standards, the International Atomic Energy Agency (IAEA) supplies low-level standards in aqueous and environmental-type matrices, for which inquiry should be directed to Analytical Quality Control Services, International Atomic Energy Agency, Kärntner Ring 11, A-1010, Vienna 1, Austria. The National Bureau of Standards (NBS) offers a custom calibration service at actual cost for certain nuclides not listed.

Sources of the listed standards are limited to the National Bureau of Standards, the British Radiochemical Centre at Amersham and its U. S. distributor – Amersham/Searle Corp., the Commissariat à l'Énergie Atomique of France, and the International Atomic Energy Agency. The Oak Ridge National Laboratory provides neither radionuclide standards nor calibrated solutions. If a radioisotope is not listed in this table, then no standard was available for that radioisotope from these suppliers at the time the table was compiled.

Suppliers should furnish (or at least be able to furnish) information on the form of the material, the method and accuracy of standardization, the properties assumed for the nuclide, and the radionuclidic purity of the preparation. This information is essential to the conscientious user; the necessity for providing this information may help the supplier to discover possible shortcomings in his own standards or unwarranted assumptions used in his calibrations. Point sources on films or plates are sometimes satisfactory, provided that the samples are always prepared in an equivalent way, but standards in solution form are usually better.

Although standards are available for some of the nuclides used in radiochemical and isotope-applications work, more are needed. The impetus to provide such standards will result only from the recognition of their value by users.

Table 13. Available Radioactivity Standards as of July 1969

Radioisotope	Standard	Radioisotope	Standard	Radioisotope	Standard
$^3\text{H}$	NBS-S, A/S, CEA	$^{82}\text{Br}$	RCC, CEA	$^{140}\text{La}$	RCC
$^{14}\text{C}$	NBS-S, A/S, CEA	$^{85}\text{Kr}$	NBS-S, CEA	$^{139}\text{Ce}$	NBS-S*, NBS-C, A/S
$^{22}\text{Na}$	NBS-S, NBS-C, A/S, IAEA*, CEA	$^{86}\text{Rb}$	A/S, CEA	$^{141}\text{Ce}$	NBS-S, NBS-C, A/S, CEA
$^{24}\text{Na}$	NBS-C, A/S, CEA	$^{85}\text{Sr}$	NBS-C, A/S, CEA	$^{143}\text{Pr}$	A/S, CEA
$^{28}\text{Mg}$ - $^{28}\text{Al}$	RCC	$^{89}\text{Sr}$	NBS-C, A/S, CEA	$^{144}\text{Ce}$ - $^{144}\text{Pr}$	NBS-S, A/S, CEA
$^{32}\text{P}$	NBS-C, A/S, IAEA*, CEA	$^{90}\text{Sr}$ - $^{90}\text{Y}$	NBS-C, A/S, CEA	$^{147}\text{Nd}$	RCC
$^{35}\text{S}$	NBS-C, A/S, CEA	$^{88}\text{Y}$	NBS-S*, NBS-C, IAEA*, A/S, CEA	$^{147}\text{Pm}$	NBS-S, NBS-C, A/S, CEA
$^{36}\text{Cl}$	NBS-S, NBS-C, A/S, CEA	$^{90}\text{Y}$	A/S, CEA	$^{160}\text{Tb}$	RCC
$^{40}\text{K}$	CEA	$^{91}\text{Y}$	A/S, CEA	$^{166}\text{Ho}$	RCC
$^{42}\text{K}$	NBS-C, A/S, CEA	$^{95}\text{Zr}$ - $^{95}\text{Nb}$	A/S, CEA	$^{170}\text{Tm}$	A/S, CEA
$^{43}\text{K}$	RCC	$^{94}\text{Nb}$	NBS-S*	$^{177}\text{Lu}$	RCC, CEA
$^{45}\text{Ca}$	NBS-C, A/S, CEA	$^{95}\text{Nb}$	NBS-S, NBS-C, A/S, CEA	$^{182}\text{Ta}$	NBS-C, RCC
$^{47}\text{Ca}$ - $^{47}\text{Sc}$	RCC	$^{99}\text{Mo}$ - $^{99m}\text{Tc}$	A/S	$^{185}\text{W}$	RCC
$^{46}\text{Sc}$	NBS-C, A/S, CEA	$^{99m}\text{Tc}$	RCC	$^{187}\text{W}$	RCC
$^{47}\text{Sc}$	RCC	$^{99}\text{Tc}$	A/S	$^{192}\text{Ir}$	RCC, CEA
$^{48}\text{V}$	RCC	$^{103}\text{Ru}$	A/S, CEA	$^{195}\text{Au}$	A/S
$^{49}\text{V}$	RCC	$^{106}\text{Ru}$ - $^{106}\text{Rh}$	A/S, CEA	$^{198}\text{Au}$	NBS-C, A/S, CEA
$^{51}\text{Cr}$	A/S, CEA	$^{105}\text{Ag}$	RCC	$^{199}\text{Au}$	RCC
$^{52}\text{Mn}$	RCC	$^{110m}\text{Ag}$	A/S, CEA	$^{197}\text{Hg}$	NBS-C, NBS-S, A/S
$^{54}\text{Mn}$	NBS-S*, NBS-C, IAEA*, A/S, CEA	$^{109}\text{Cd}$	A/S, NBS-S*	$^{203}\text{Hg}$	NBS-S, NBS-C, IAEA*, A/S, CEA
$^{52}\text{Fe}$	RCC	$^{113}\text{Sn}$ - $^{113m}\text{In}$	NBS-S, IAEA*	$^{204}\text{Tl}$	NBS-C, A/S, CEA
$^{55}\text{Fe}$	NBS-S, A/S, CEA	$^{114m}$ - $^{114}\text{In}$	A/S	$^{210}\text{Pb}$ - $^{210}\text{Bi}$	A/S
$^{59}\text{Fe}$	NBS-C, A/S, CEA	$^{122}\text{Sb}$	RCC	$^{210}\text{Po}$	NBS-S*, NBS-C, A/S, CEA
$^{57}\text{Co}$	NBS-C, A/S, IAEA*, CEA	$^{124}\text{Sb}$	RCC, CEA	$^{226}\text{Ra}$	NBS-S, NBS-C, RCC
$^{58}\text{Co}$	A/S, CEA	$^{125}\text{Sb}$	RCC	$^{228}\text{Th}$	RCC, NBS-C, NBS-S*
$^{60}\text{Co}$	NBS-S*, NBS-C, A/S, IAEA*, CEA	$^{125}\text{I}$	NBS-S, A/S, CEA	$^{233}\text{U}$	CEA
$^{63}\text{Ni}$	A/S, NBS-S, CEA	$^{131}\text{I}$	NBS-C, A/S, CEA	$^{235}\text{U}$	NBS-S
$^{64}\text{Cu}$	RCC	$^{132}\text{I}$	RCC	$^{237}\text{Np}$	RCC
$^{65}\text{Zn}$	NBS-S*, NBS-C, A/S, CEA	$^{131}\text{Cs}$	A/S, CEA	$^{239}\text{Pu}$	A/S, NBS-S, NBS-C, CEA
$^{76}\text{As}$	RCC, CEA	$^{132}\text{Cs}$	RCC	$^{241}\text{Am}$	NBS-S*, NBS-C, IAEA*, A/S, CEA
$^{77}\text{As}$	RCC, CEA	$^{134}\text{Cs}$	A/S, CEA		
$^{75}\text{Se}$	A/S, CEA	$^{137}\text{Cs}$ - $^{137m}\text{Ba}$	NBS-S*, NBS-C, A/S, IAEA*, CEA		
		$^{131}\text{Ba}$ - $^{131}\text{Cs}$	RCC		
		$^{133}\text{Ba}$	A/S, CEA		
		$^{140}\text{Ba}$ - $^{140}\text{La}$	A/S, CEA		

A/S Available from Amersham/Searle Corp., 2000 Nuclear Drive, Des Plaines, Illinois 60018.

IAEA Available from International Atomic Energy Agency, Kärntner Ring 11, A-1010, Vienna 1, Austria.

NBS-C Calibration service is available from U.S. Department of Commerce, National Bureau of Standards, Washington, D.C. 20234.

NBS-S Available from U.S. Department of Commerce, National Bureau of Standards, Washington, D.C. 20234.

RCC Available from the Radiochemical Centre, Amersham, Buckinghamshire, England.

CEA Available from Commissariat à l'Énergie Atomique, Gif-sur-Yvette, France.

\* Available only as a solid source.

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## PEACEFUL USES OF RADIOISOTOPES

Alpha, beta, and gamma radiations are responsible in one way or another for the peaceful uses of radioisotopes. Figure 15 illustrates the basic principles of these various uses. Typical applications are:

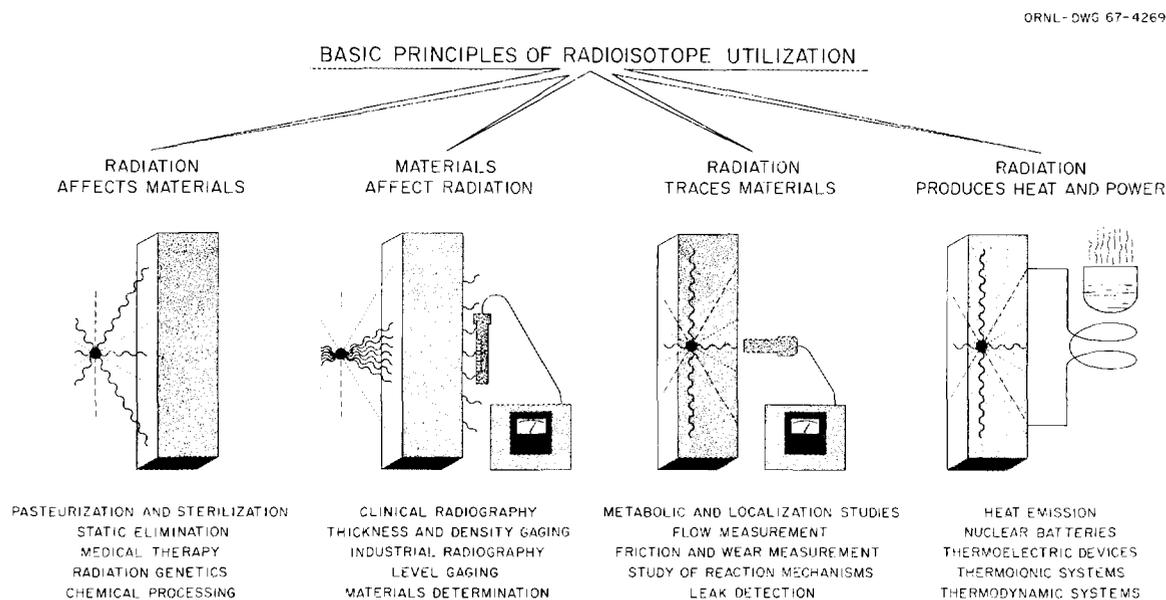


Fig. 15. Basic Principles of Radioisotope Use.

1. **Process Radiation.** Cobalt-60 and  $^{137}\text{Cs}$  are used in large quantities to sterilize goat hair, medical supplies, and foods; to inhibit ripening and spoilage of fruits and vegetables; to inhibit sprouting of potatoes and onions; and to disinfest grains (Fig. 16). Gamma rays can be used to initiate chemical reactions such as polymerization or to catalyze reactions such as that between  $\text{HBr}$  and ethylene to produce ethyl bromide. The rays are also used to induce plant mutations.
2. **Tracing.** Numerous isotopes are used to follow process streams, to study reaction kinetics and mechanisms, to investigate metabolic processes, to locate leaks, to measure flow rates, to study friction and wear and laundering efficiency, and to help assay pharmaceuticals.
3. **Gaging.** The absorption or reflection of radiation by materials allows the use of isotopes in detecting liquid or solid levels, measuring thicknesses or densities (including, for example, soil density), and radiographing. Since no contact with the material being studied is necessary, the method not only is nondestructive (Fig. 17), but also can be made continuous and a part of an automated system.
4. **Static Elimination and Luminescent Devices.** The radiations from isotopes ionize air in passing through it, and the ions then neutralize static charges, thereby eliminating the static. Beta radiations, in particular, can be used in conjunction with phosphors to make long-lasting luminescent devices such as exit signs (Fig. 18) and locks.
5. **Thermal Applications.** The heat from radioisotope decay can be used directly or indirectly (as electricity after conversion by thermoelectric devices) to heat swimsuits, to activate heart pacemakers, to power heart-assist devices, and to provide the energy needed for operating unmanned navigation aids (Fig. 19), weather stations, and satellites.

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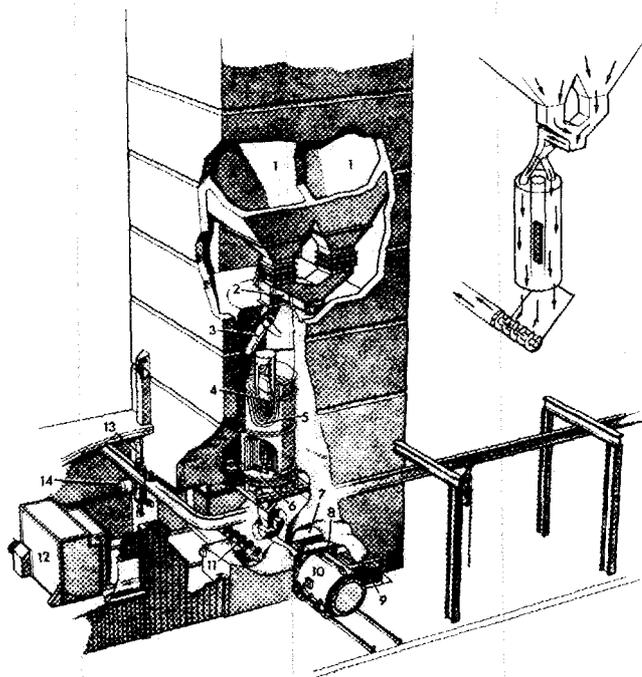


Fig. 16. Schematic of a Planned Grain Irradiator.

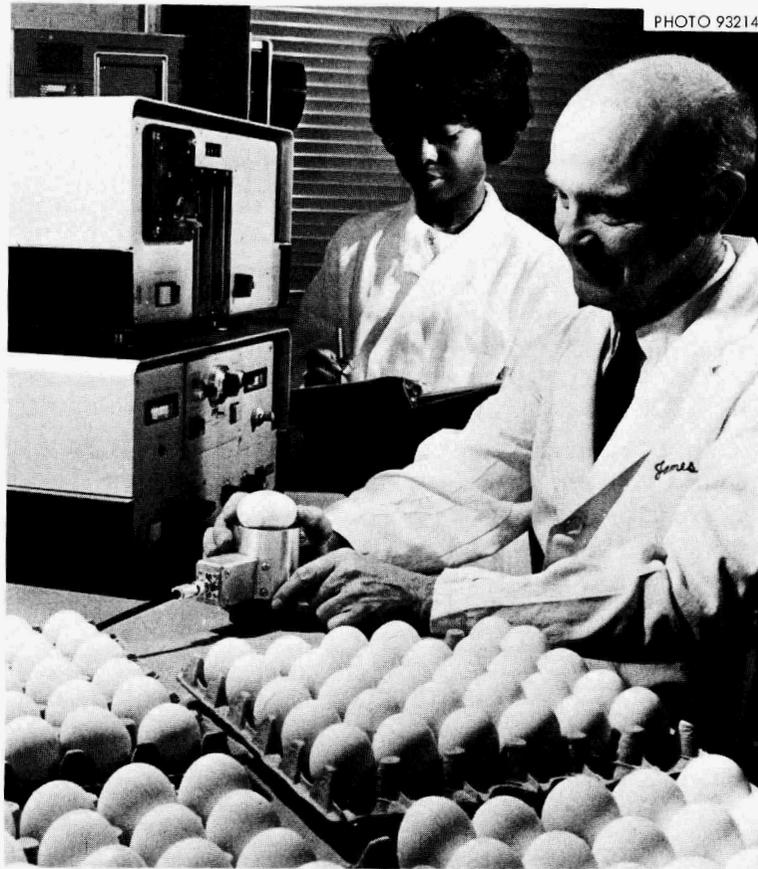


Fig. 17. Eggshell Testing Gage Used by USDA to Evaluate Strength of Shell.

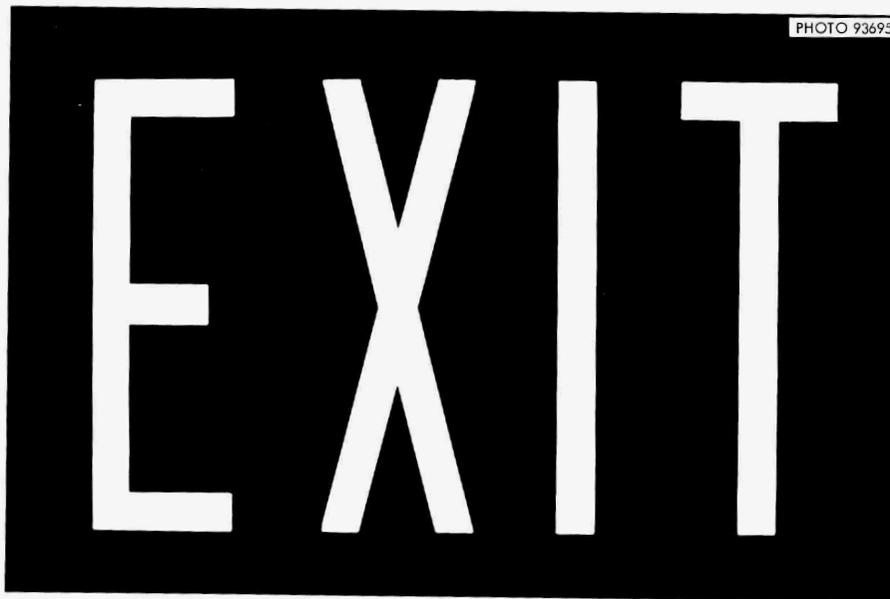


Fig. 18. Beta-Excited Luminescent Exit Sign.

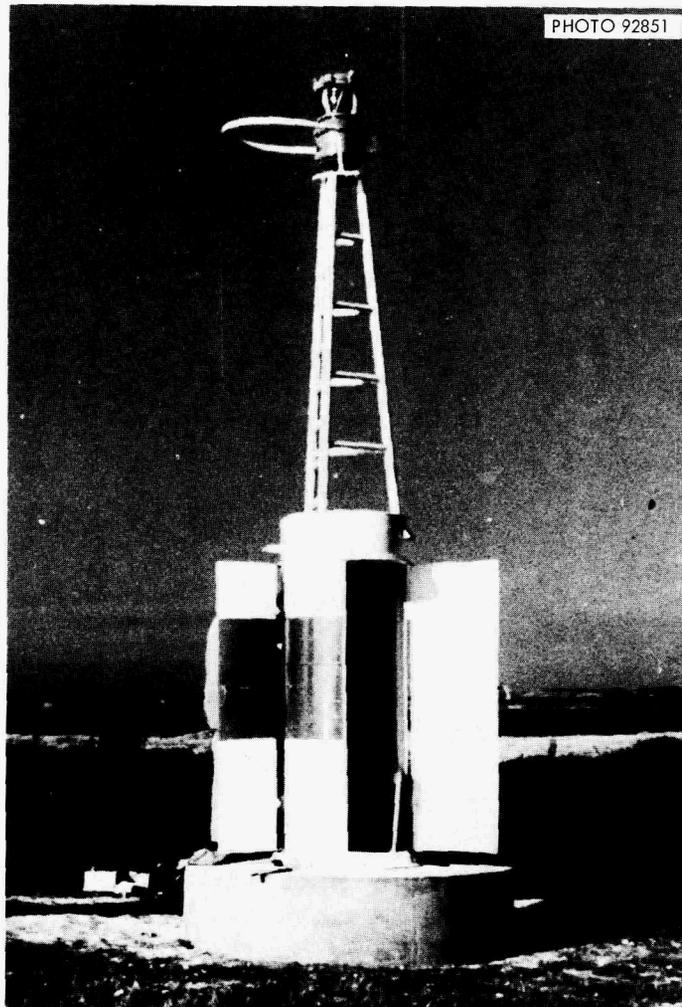


Fig. 19. Navigational Light on the Coast of Zeeland, Denmark, Powered by a Radioisotope Heat Source.

#### LIST OF AVAILABLE RADIOISOTOPES, WITH PRINCIPAL CHARACTERISTICS

In the following pages, principal characteristics of selected radioisotopes are summarized. Half-lives are given in seconds, minutes, hours, days, and years. Decay modes include alpha ( $\alpha$ ), negatron ( $\beta^-$ ), positron ( $\beta^+$ ), orbital-electron capture (EC), gamma ( $\gamma$ ), and conversion electron ( $e^-$ ). The symbol  $\gamma^\pm$  refers to 0.511-MeV annihilation from positron emitters, and IT indicates the occurrence of isomeric transition. (Particle types are not identified under "Decay Energies and Abundances," since they are specified under "Decay Modes.") Percentages show the branching between different modes of decay, for example, between EC and  $\beta^+$ . When given with energies, percentages (in parentheses) apply to discrete radiations in the case of alpha and unconverted gamma and to groups of positrons or negatrons having indicated *maximum* energies. A distinction should be made between a gamma *transition* characterized by a certain energy and the *unconverted* gamma actually emitted. A certain *conversion coefficient*,  $\alpha (=N_e/N_\gamma)$ , applies to each gamma transition. The percentage of gamma emitted,  $u$ , may be defined as  $u = B/(1 + \alpha)$ , where  $B$  = percentage of

transition. Note that  $\alpha$  can vary from essentially zero to a large value, with corresponding variation of  $u$  from  $B$  (sometimes 100%) to  $\sim 0$ .

A pragmatic approach was taken in deciding what radiations to list. In general those appearing in less than 5% of the decays of a given nuclide were not listed, although their presence is indicated by the term "Others." Exceptions were made in many cases. Gammas giving rise to major peaks in a NaI(Tl) spectrum were included, and combined percentages were usually given for those not resolved by a NaI(Tl) spectrometer, even though they would be resolved by a Ge(Li) spectrometer. X rays are mentioned where important, but no attempt was made to calculate percentages.

Decay scheme data were taken from recent compilations<sup>1-5</sup> and current literature. A useful table of theoretical conversion coefficients has been issued.<sup>6</sup> In the numerous cases of disagreement, choices – sometimes arbitrary – were made, generally weighted in favor of recent data.\* For half-lives, in addition to the above compilations, much data came from recent reports and articles.<sup>7-10</sup>

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\*Members of the Nuclear Data Group, Oak Ridge National Laboratory, especially M. J. Martin, have kindly made available compiled information and selections in advance of publication.

Isotope	Half-Life	Production Method(s)	Decay Mode(s)	Decay Energies (MeV) and Abundances (%) <sup>a</sup>	
				Particles	Photons
Actinium-227	21.8 y	Natural decay of <sup>235</sup> U chain <sup>26</sup> Mg(p,n) <sup>26</sup> Al	$\beta^-$	0.045	
Aluminum-26	$7.4 \times 10^5$ y		$\beta^+$ (85%), EC (15%), $\gamma$	1.17 (85)	$\gamma^\pm$ (170) 1.81 (100) Mg x rays
Americium-241	433 y	<sup>241</sup> Pu $\xrightarrow[\text{(14.2 y)}]{\beta^-}$ <sup>241</sup> Am	$\alpha, \gamma, e^-$	5.49 (85) 5.44 (13)	0.060 (36) Np L x rays
Antimony-122	2.7 d	<sup>121</sup> Sb(n, $\gamma$ ) <sup>122</sup> Sb	$\beta^-$ (97%), EC (3%), $\gamma$	0.74 (4) 1.40 (63) 1.97 (30)	0.56 (66) 0.69 (3)
Antimony-124	60.2 d	<sup>123</sup> Sb(n, $\gamma$ ) <sup>124</sup> Sb	$\beta^-, \gamma$	0.24 (11) 0.61 (51) 0.95 (5) 1.60 (7) 2.31 (23) Others	0.60 (98) 0.64 (7) 0.72 (14) 1.30 (6) 1.69 (48) 2.09 (6)
Antimony-125	2.7 y	<sup>124</sup> Sn(n, $\gamma$ ) <sup>125</sup> Sn $\xrightarrow[\text{(9.4 d)}]{\beta^-}$ <sup>125</sup> Sb	$\beta^-, \gamma$	0.12 (37) 0.30 (40) 0.44 (6) 0.62 (13) Others	0.175 (6) 0.43–0.46 (40) 0.60–0.64 (35)
Argon-37	35 d	<sup>40</sup> Ca(n, $\alpha$ ) <sup>37</sup> Ar	EC		Cl x rays
Argon-39	~265 y	<sup>39</sup> K(n,p) <sup>39</sup> Ar	$\beta^-$	0.56	
Arsenic-73	80 d	<sup>73</sup> Ge(p,n) <sup>73</sup> As	EC, $\gamma, e^-$		0.054 (~11) Ge x rays
Arsenic-74	17.8 d	<sup>71</sup> Ga( $\alpha, n$ ) <sup>74</sup> As <sup>74</sup> Ge(p,n) <sup>74</sup> As <sup>74</sup> Se(n,p) <sup>74</sup> As	EC (39%), $\beta^+$ (29%), $\beta^-$ (32%), $\gamma$	$\beta^+$ : 0.91 (26) 1.5 (3) $\beta^-$ : 0.72 (14) 1.36 (18)	$\gamma^\pm$ (58) 0.60 (61) 0.64 (14) Ge x rays
Arsenic-76	26.4 h	<sup>75</sup> As(n, $\gamma$ ) <sup>76</sup> As	$\beta^-, \gamma$	1.20 (7) 1.76 (4) 2.41 (31) 2.96 (56)	0.56 (45) 0.65 (6) 1.22 (6)

<sup>a</sup>Abundances are given in parentheses.

Isotope	Half-Life	Production Method(s)	Decay Mode(s)	Decay Energies (MeV) and Abundances (%) <sup>a</sup>	
				Particles	Photons
Arsenic-77	38.7 h	$^{76}\text{Ge}(n,\gamma)^{77}\text{Ge} \xrightarrow[\text{(11.3 h)}]{\beta^-} ^{77}\text{As}$	$\beta^-, \gamma$	0.16 (3) 0.44 (3) 0.68 (94) Others	0.24 (2.5) 0.52 (0.8) Others
Barium-131- Cesium-131	$^{131}\text{Ba}$ , 12 d; $^{131}\text{Cs}$ , 9.7 d	$^{130}\text{Ba}(n,\gamma)^{131}\text{Ba} \xrightarrow[\text{(12 d)}]{\text{EC}} ^{131}\text{Cs}$	EC, $\gamma$ , $e^-$ ; EC		$^{131}\text{Ba}$ : 0.13 (28) 0.22 (28) 0.38 (16) 0.50 (60) 0.60 (3) Cs x rays Others $^{131}\text{Cs}$ : Xe x rays
Barium-133	10.7 y	$^{132}\text{Ba}(n,\gamma)^{133}\text{Ba}$ , using target enriched in $^{132}\text{Ba}$	EC, $\gamma$ , $e^-$		0.081 (36) 0.28 (7) 0.30 (19) 0.36 (63) 0.38 (9) Cs x rays
Barium-140- Lanthanum-140	$^{140}\text{Ba}$ , 12.8 d; $^{140}\text{La}$ , 40.2 h	Fission product $^{140}\text{Ba} \xrightarrow[\text{(12.8 d)}]{\beta^-} ^{140}\text{La}$	$\beta^-, \gamma; \beta^-, \gamma$	$^{140}\text{Ba}$ : 0.48 (25) 0.6 (10) 0.9 (5) 1.01 (60) $^{140}\text{La}$ : 1.10 (26) 1.38 (45) 1.71 (10) 2.20 (7) Others	0.030 0.162 (6) 0.30 (4) 0.43 (5) 0.54 (~30) 0.33 (20) 0.49 (40) 0.82 (23) 0.92 (10) 1.60 (95)
Beryllium-7	53 d	$^7\text{Li}(p,n)^7\text{Be}$	EC, $\gamma$		0.48 (10) Li x rays
Beryllium-10	$2.7 \times 10^6$ y	$^9\text{Be}(n,\gamma)^{10}\text{Be}$	$\beta^-$	0.55	

<sup>a</sup>Abundances are given in parentheses.

Isotope	Half-Life	Production Method(s)	Decay Mode(s)	Decay Energies (MeV) and Abundances (%) <sup>a</sup>	
				Particles	Photons
Bismuth-206	6.24 d	$^{207}\text{Pb}(p, 2n)^{206}\text{Bi}$ $^{206}\text{Pb}(p, n)^{206}\text{Bi}$	EC, $\gamma$ , $e^-$		0.18 (21) 0.34 (25) 0.50–0.54 (94) 0.80 (100) 0.88–0.90 (87) 1.72 (34) Pb x rays Others
Bismuth-207	30 y	$^{207}\text{Pb}(p, n)^{207}\text{Bi}$	EC, $\gamma$		0.57 (98) 1.06 (77) 1.77 (8) Pb x rays
Bismuth-210 [Note: contains $^{210}\text{Po}$ daughter]	5.0 d	$^{209}\text{Bi}(n, \gamma)^{210}\text{Bi}$	$\beta^-$	1.17	
Bromine-77	56 h	$^{75}\text{As}(\alpha, 2n)^{77}\text{Br}$	EC, $\gamma$ , $e^-$		0.24 (30) 0.30 (6) 0.52 (23) 0.58 (7) Se x rays Others
Bromine-82	35.4 h	$^{81}\text{Br}(n, \gamma)^{82}\text{Br}$	$\beta^-$ , $\gamma$	0.44 (98) Others	0.55 (72) 0.62 (44) 0.70 (27) 0.78 (83) 0.83 (24) 1.04 (29) 1.32 (27) 1.47 (17)
Cadmium-109– Silver-109 <sup>m</sup>	$^{109}\text{Cd}$ , 1.26 y; $^{109\text{m}}\text{Ag}$ , 40 s	$^{107}\text{Ag}(n, \gamma)^{108}\text{Ag}$ $\beta^-$ (2.4 m) $^{108}\text{Cd}(n, \gamma)^{109}\text{Cd} \xrightarrow{\text{EC (1.26 y)}} ^{109\text{m}}\text{Ag}$ $^{108}\text{Cd}(n, \gamma)^{109}\text{Cd}$ , $^{109}\text{Ag}(p, n)^{109}\text{Cd}$	EC, $\gamma$ , $e^-$ ; IT		0.088 (4) Ag x rays

<sup>a</sup>Abundances are given in parentheses.

Isotope	Half-Life	Production Method(s)	Decay Mode(s)	Decay Energies (MeV) and Abundances (%) <sup>a</sup>	
				Particles	Photons
Cadmium-113m	14 y	$^{112}\text{Cd}(n,\gamma)^{113m}\text{Cd}$ $^{113}\text{Cd}(n,n')^{113m}\text{Cd}$	$\beta^-$	0.58	0.27 (~0.1)
Cadmium-115m	43 d	$^{114}\text{Cd}(n,\gamma)^{115m}\text{Cd}$	$\beta^-, \gamma$	1.6 (97) Others	0.49 (0.3) 0.94 (1.9) 1.29 (0.9)
Cadmium-115– Indium-115m	$^{115}\text{Cd}$ , 55 h; $^{115m}\text{In}$ , 4.5 h	$^{114}\text{Cd}(n,\gamma)^{115}\text{Cd} \xrightarrow[(55\text{ h})]{\beta^-} ^{115m}\text{In}$	$\beta^-, \gamma$ ; $\beta^-, \gamma, \text{IT}, e^-$	$^{115}\text{Cd}$ : 0.6 (~37) 1.11 (~62) $^{115m}\text{In}$ : 0.84 (5)	0.49 (~10) 0.52 (~26) 0.34 (49) In x rays
Calcium-45	164 d	$^{44}\text{Ca}(n,\gamma)^{45}\text{Ca}$	$\beta^-$	0.26	
Calcium-47– Scandium-47	$^{47}\text{Ca}$ , 4.53 d; $^{47}\text{Sc}$ , 3.4 d	$^{46}\text{Ca}(n,\gamma)^{47}\text{Ca} \xrightarrow[(4.53\text{ d})]{\beta^-} ^{47}\text{Sc}$ , using target enriched in $^{46}\text{Ca}$	$\beta^-, \gamma$ ; $\beta^-, \gamma$	$^{47}\text{Ca}$ : 0.69 (82) 1.99 (18) $^{47}\text{Sc}$ : 0.44 (70) 0.60 (30)	0.49 (7) 0.81 (7) 1.30 (76) 0.16 (70)
Carbon-14	$5.73 \times 10^3$ y	$^{14}\text{N}(n,p)^{14}\text{C}$	$\beta^-$	0.156	
Cerium-139	138 d	$^{139}\text{La}(p,n)^{139}\text{Ce}$	EC, $\gamma, e^-$		0.17 (80) La x rays
Cerium-141	32.5 d	Fission product $^{139}\text{La}(n,\gamma)^{140}\text{La}(n,\gamma)^{141}\text{La} \xrightarrow[(3.9\text{ h})]{\beta^-} ^{141}\text{Ce}$	$\beta^-, \gamma$	0.44 (70) 0.58 (30)	0.145 (49)
Cerium-143 [Note: contains $^{143}\text{Pr}$ daughter]	33 h	$^{142}\text{Ce}(n,\gamma)^{143}\text{Ce}$	$\beta^-, \gamma, e^-$	1.09 (50) 1.39 (30) Others	0.057 (11) 0.29 (46) 0.66 (7) 0.72 (7) Pr x rays Others
Cerium-144– Praseodymium-144	$^{144}\text{Ce}$ , 284 d; $^{144}\text{Pr}$ , 17 m	Fission product $^{144}\text{Ce} \xrightarrow[(284\text{ d})]{\beta^-} ^{144}\text{Pr}$	$\beta^-, \gamma, e^-$ ; $\beta^-, \gamma$	$^{144}\text{Ce}$ : 0.19 (20) 0.24 (8) 0.32 (72) $^{144}\text{Pr}$ : 2.97 (98) Others	0.080 (2) 0.134 (11) 0.69 (1.5) 1.5 (0.3) 2.2 (0.7)

<sup>a</sup>Abundances are given in parentheses.

Isotope	Half-Life	Production Method(s)	Decay Mode(s)	Decay Energies (MeV) and Abundances (%) <sup>a</sup>	
				Particles	Photons
Cesium-131	9.7 d	$^{130}\text{Ba}(n,\gamma)^{131}\text{Ba} \xrightarrow{(12\text{ d})} ^{131}\text{Cs}$	EC		Xe x rays
Cesium-132	6.5 d	$^{133}\text{Cs}(p,pn)^{132}\text{Cs}$	EC (98%), $\beta^-$ (2%), $\gamma$	~0.7 (~2)	0.67 (98) Xe x rays
Cesium-134	2.07 y	$^{133}\text{Cs}(n,\gamma)^{134}\text{Cs}$	$\beta^-$ , $\gamma$	0.09 (27) 0.66 (71) Others	0.57 (26) 0.60 (98) 0.80 (95) Others
Cesium-137– Barium-137m	$^{137}\text{Cs}$ , 30 y; $^{137m}\text{Ba}$ , 2.6 m	Fission product $^{137}\text{Cs} \xrightarrow{(30\text{ y})} ^{137m}\text{Ba}$	$\beta^-$ ; IT	$^{137}\text{Cs}$ : 0.51 (95) 1.17 (5)	$^{137m}\text{Ba}$ : 0.662 (90) <sup>b</sup> Ba x rays
Chlorine-36	$3.0 \times 10^5$ y	$^{35}\text{Cl}(n,\gamma)^{36}\text{Cl}$	$\beta^-$ (98%), EC (2%)	0.71 (98)	S x rays
Chlorine-38	37.3 m	$^{37}\text{Cl}(n,\gamma)^{38}\text{Cl}$	$\beta^-$ , $\gamma$	1.10 (31) 2.75 (11) 4.91 (58)	1.64 (31) 2.17 (42)
Chromium-51	27.8 d	$^{51}\text{V}(p,n)^{51}\text{Cr}$ $^{50}\text{Cr}(n,\gamma)^{51}\text{Cr}$ , using target enriched in $^{50}\text{Cr}$	EC, $\gamma$		0.32 (10) V x rays
Cobalt-56	77.3 d	$^{56}\text{Fe}(p,n)^{56}\text{Co}$	EC (77%), $\beta^+$ (23%), $\gamma$	1.46 (22) Others	$\gamma^+$ (46) 0.85 (100) 1.04 (13) 1.24 (69) 1.77 (16) 2.04 (7) 2.60 (17) 3.25 (8) Fe x rays Others
Cobalt-57	270 d	$^{60}\text{Ni}(p,\alpha)^{57}\text{Co}$	EC, $\gamma$ , $e^-$		0.014 (9) 0.122 (86) 0.136 (11) Fe x rays
Cobalt-58	71 d	$^{58}\text{Ni}(n,p)^{58}\text{Co}$ $^{55}\text{Mn}(\alpha,n)^{58}\text{Co}$	$\beta^+$ (15%), EC (85%), $\gamma$	0.47 (15)	$\gamma^+$ (30) 0.81 (99) Fe x rays

<sup>a</sup>Abundances are given in parentheses.

<sup>b</sup>85% of total  $^{137}\text{Cs}$  beta.

Isotope	Half-Life	Production Method(s)	Decay Mode(s)	Decay Energies (MeV) and Abundances (%) <sup>a</sup>	
				Particles	Photons
Cobalt-60	5.26 y	<sup>59</sup> Co(n,γ) <sup>60</sup> Co <sup>60</sup> Ni(n,p) <sup>60</sup> Co	β <sup>-</sup> , γ	0.32	1.17 (100) 1.33 (100)
Copper-64	12.7 h	<sup>63</sup> Cu(n,γ) <sup>64</sup> Cu	β <sup>-</sup> (39%), β <sup>+</sup> (19%), EC (42%), γ	0.57 (39) 0.66 (19)	γ <sup>±</sup> (38) 1.34 (0.6) Ni x rays
Copper-67	61.7 h	<sup>67</sup> Zn(n,p) <sup>67</sup> Cu	β <sup>-</sup> , γ	0.40 (45) 0.48 (35) 0.58 (20)	0.09 (~24) 0.18 (~43)
Curium-242	163 d	<sup>241</sup> Am(n,γ) <sup>242</sup> Am $\xrightarrow{(16\text{ h})} \beta^-$ <sup>242</sup> Cm	α, γ, e <sup>-</sup>	6.11 (74) 6.07 (26)	0.044 (0.04) Pu L x rays Others
Curium-244	18.1 y	<sup>243</sup> Am(n,γ) <sup>244</sup> Am $\xrightarrow{(10\text{ h})} \beta^-$ <sup>244</sup> Cm	α, γ, e <sup>-</sup>	5.81 (77) 5.77 (23)	0.043 (0.02) Pu L x rays Others
Dysprosium-159	~144 d	<sup>158</sup> Dy(n,γ) <sup>159</sup> Dy	EC, γ, e <sup>-</sup>		0.058 (~3) Tb x rays
Dysprosium-165	2.35 h	<sup>164</sup> Dy(n,γ) <sup>165</sup> Dy	β <sup>-</sup> , γ	1.20 (~14) 1.29 (~83)	0.095 (3.8) Ho x rays Others
Erbium-169	9.3 d	<sup>168</sup> Er(n,γ) <sup>169</sup> Er	β <sup>-</sup> , γ, e <sup>-</sup>	0.33 (42) 0.34 (58)	0.008 (~0.3) Tm M x rays
Erbium-171	7.5 h	<sup>170</sup> Er(n,γ) <sup>171</sup> Er	β <sup>-</sup> , γ, e <sup>-</sup>	1.05 (93) Others	0.11–0.12 (33) 0.30–0.31 (92) Tm x rays Others
Europium-150	12.8 h	<sup>150</sup> Sm(p,n) <sup>150</sup> Eu	β <sup>-</sup> (~90%), EC (~9%), γ, e <sup>-</sup>	1.0 (~90)	0.33 (4) 0.41 (3) Sm x rays Others
Europium-152m <sub>1</sub>	9.3 h	<sup>151</sup> Eu(n,γ) <sup>152m1</sup> Eu	β <sup>-</sup> (77%), EC (23%), γ, e <sup>-</sup>	1.87 (74) Others	0.12 (7) 0.84 (12) 0.96 (12) Sm x rays

<sup>a</sup>Abundances are given in parentheses.

Isotope	Half-Life	Production Method(s)	Decay Mode(s)	Decay Energies (MeV) and Abundances (%) <sup>a</sup>	
				Particles	Photons
Europium-152– Europium-154	<sup>152</sup> Eu, <sup>b</sup> 12.7 y; <sup>154</sup> Eu, <sup>b</sup> 16 y	<sup>151</sup> Eu(n,γ) <sup>152</sup> Eu <sup>153</sup> Eu(n,γ) <sup>154</sup> Eu	β <sup>-</sup> (27%), EC (73%), γ, e <sup>-</sup> ; β <sup>-</sup> , γ, e <sup>-</sup>	<sup>152</sup> Eu: 0.70 (12) 1.48 (6) Others	0.12 (30) 0.34 (23) 0.78 (13) 0.97 (14) 1.09–1.11 (29) 1.41 (25) Others Gd x rays Sm x rays
Europium-155	1.81 y <sup>b</sup>	<sup>154</sup> Sm(n,γ) <sup>155</sup> Sm $\xrightarrow{(22\text{ m})} \beta^-$ <sup>155</sup> Eu	β <sup>-</sup> , γ, e <sup>-</sup>	<sup>154</sup> Eu: 0.26 (28) 0.58 (38) 0.87 (24) 1.86 (10)	0.12 (32) 0.72 (20) 0.87 (15) 1.00–1.01 (30) 1.28 (38) Gd x rays Others
Fluorine-18	110 m	<sup>19</sup> F(p,pn) <sup>18</sup> F	β <sup>+</sup> (97%), EC (3%)	0.14 (~43) 0.16 (~32) 0.19 (~10) 0.25 (~15)	0.087 (32) 0.105 (20) Gd x rays
Gadolinium-148	88 y	<sup>147</sup> Sm(α,3n) <sup>148</sup> Gd <sup>151</sup> Eu(p,4n) <sup>148</sup> Gd	α	0.63 (97) 3.18	γ <sup>±</sup> (194)
Gadolinium-153	240 d	<sup>152</sup> Gd(n,γ) <sup>153</sup> Gd <sup>151</sup> Eu(n,γ) <sup>152m1</sup> Eu $\beta^-$ (9.3 h) <sup>152</sup> Gd(n,γ) <sup>153</sup> Gd	EC, γ, e <sup>-</sup>		0.10 (52) Eu x rays
Gadolinium-159	18 h	<sup>158</sup> Gd(n,γ) <sup>159</sup> Gd	β <sup>-</sup> , γ, e <sup>-</sup>	0.59 (13) 0.89 (24) 0.95 (63)	0.058 (~4) 0.36 (~12) Tb x rays
Gallium-66	9.5 h	<sup>63</sup> Cu(α,n) <sup>66</sup> Ga	β <sup>+</sup> (57%), EC (43%), γ	0.93 (~4) 4.15 (~51)	γ <sup>±</sup> (114) 1.04 (37) 2.75 (25) Zn x rays Others

<sup>a</sup>Abundances are given in parentheses.

<sup>b</sup>Current measurements indicate 13.9 y for <sup>152</sup>Eu, 7.9 y for <sup>154</sup>Eu, and 4.9 y for <sup>155</sup>Eu, but these values have not been firmly established.

Isotope	Half-Life	Production Method(s)	Decay Mode(s)	Decay Energies (MeV) and Abundances (%) <sup>a</sup>	
				Particles	Photons
Gallium-67	78 h	$^{67}\text{Zn}(p,n)^{67}\text{Ga}$	EC, $\gamma$ , $e^-$		0.093 (40) 0.18 (24) 0.30 (22) 0.39 (7) Zn x rays
Gallium-72	14.1 h	$^{71}\text{Ga}(n,\gamma)^{72}\text{Ga}$	$\beta^-$ , $\gamma$	0.7 (40) 1.0 (31) 1.5 (7) 2.54 (7) 3.16 (7) Others	0.63 (26) 0.84 (93) 0.90 (10) 2.20 (29) 2.5 (21) Others
Germanium-68– Gallium-68	$^{68}\text{Ge}$ , 280 d; $^{68}\text{Ga}$ , 68m	$^{69}\text{Ga}(p,2n)^{68}\text{Ge} \xrightarrow{(280\text{ d})\text{EC}} ^{68}\text{Ga}$	EC; EC (13%), $\beta^+$ (87%), $\gamma$	$^{68}\text{Ga}$ : 1.89 (85)	$^{68}\text{Ga}$ : $\gamma^\pm$ (174) 1.08 (4) Zn x rays $^{68}\text{Ge}$ : Ga x rays
Germanium-71	11.4 d	$^{70}\text{Ge}(n,\gamma)^{71}\text{Ge}$	EC		Ga x rays
Germanium-77 [Note: contains $^{77}\text{As}$ daughter]	11.3 h	$^{76}\text{Ge}(n,\gamma)^{77}\text{Ge}$	$\beta^-$ , $\gamma$	0.79 (8) 1.23 (13) 1.60 (22) 2.16 (24) 2.32 (15) Others	0.21–0.22 (60) 0.26 (45) 0.37 (15) 0.42 (25) 0.56 (18) 0.63 (11) Others
Gold-195	183 d	$^{195}\text{Pt}(p,n)^{195}\text{Au}$	EC, $\gamma$ , $e^-$		0.099 (~9) Pt x rays
Gold-198	2.70 d	$^{197}\text{Au}(n,\gamma)^{198}\text{Au}$	$\beta^-$ , $\gamma$	0.29 (1) 0.97 (99)	0.41 (96) 0.68 (1)
Gold-199	3.15 d	$^{198}\text{Pt}(n,\gamma)^{199}\text{Pt} \xrightarrow{(31\text{ m})\beta^-} ^{199}\text{Au}$	$\beta^-$ , $\gamma$ , $e^-$	0.25 (23) 0.30 (70) 0.46 (7)	0.16 (37) 0.21 (8) Hg x rays
Hafnium-175	70 d	$^{174}\text{Hf}(n,\gamma)^{175}\text{Hf}$	EC, $\gamma$ , $e^-$		0.34 (85) Lu x rays Others

<sup>a</sup>Abundances are given in parentheses.

Isotope	Half-Life	Production Method(s)	Decay Mode(s)	Decay Energies (MeV) and Abundances (%) <sup>a</sup>	
				Particles	Photons
Hafnium-181	42.5 d	$^{180}\text{Hf}(n,\gamma)^{181}\text{Hf}$	$\beta^-$ , $\gamma$	0.41 (93) Others	0.13 (~48) 0.35 (~13) 0.48 (~81)
Holmium-166	27.0 h	$^{165}\text{Ho}(n,\gamma)^{166}\text{Ho}$	$\beta^-$ , $\gamma$ , $e^-$	1.76 (~47) 1.84 (~52)	0.080 (6) Er x rays Others
Holmium-166m	$1.2 \times 10^3$ y	$^{165}\text{Ho}(n,\gamma)^{166m}\text{Ho}$	$\beta^-$ , $\gamma$ , $e^-$	~0.01 (~15) ~0.06 (~85)	0.081 (12) 0.18 (90) 0.28 (30) 0.41 (12) 0.53 (12) 0.71 (58) 0.81-0.83 (71) Er x rays Others
Hydrogen-3	12.3 y	$^6\text{Li}(n,\alpha)^3\text{H}$	$\beta^-$	0.018	0.17 (88) 0.25 (94) Cd x rays
Indium-111	67.4 h	$^{111}\text{Cd}(p,n)^{111}\text{In}$	EC, $\gamma$ , $e^-$		$^{114}\text{In}$ : 1.98 (99) $^{114m}\text{In}$ : 0.19 (~17) In x rays Others
Indium-114m-Indium-114	$^{114m}\text{In}$ , 50 d; $^{114}\text{In}$ , 72 s	$^{113}\text{In}(n,\gamma)^{114m}\text{In} \xrightarrow{(50\text{ d})} ^{114}\text{In}$	IT (97%), EC (3%), $e^-$ ; $\beta^-$ (99%), EC (1%)		
Indium-116m <sub>1</sub>	54 m	$^{115}\text{In}(n,\gamma)^{116m_1}\text{In}$	$\beta^-$ , $\gamma$	0.60 (~20) 0.87 (~30) 1.00 (~50)	0.42 (~36) 1.09 (54) 1.29 (80) 2.1 (20) Others
Iodine-123	13 h	$^{123}\text{Te}(p,n)^{123}\text{I}$	EC, $\gamma$ , $e^-$		0.16 (83) Te x rays
Iodine-124	4.2 d	$^{121}\text{Sb}(\alpha,n)^{124}\text{I}$	EC (75%), $\beta^+$ (25%), $\gamma$	1.5 (14) 2.1 (11)	$\gamma^\pm$ (50) 0.60 (66) 1.69 (14) Te x rays Others

<sup>a</sup>Abundances are given in parentheses.

Isotope	Half-Life	Production Method(s)	Decay Mode(s)	Decay Energies (MeV) and Abundances (%) <sup>a</sup>	
				Particles	Photons
Iodine-125	60 d	$^{124}\text{Xe}(n,\gamma)^{125}\text{Xe} \xrightarrow{(18\text{ h})} ^{125}\text{I}$	EC, $\gamma$ , $e^-$		0.035 (7) Te x rays
Iodine-126	13 d	$^{126}\text{Te}(p,n)^{126}\text{I}$	EC (55%), $\beta^-$ (44%), $\gamma$	0.39 (5) 0.87 (30) 1.25 (9)	0.39 (34) 0.66 (33) Te x rays
Iodine-129	$1.6 \times 10^7$ y	Fission product	$\beta^-$ , $\gamma$ , $e^-$	0.15	0.040 (7) Xe x rays
Iodine-130	12.3 h	$^{129}\text{I}(n,\gamma)^{130}\text{I}$ $^{130}\text{Te}(p,n)^{130}\text{I}$	$\beta^-$ , $\gamma$	0.60 (47) 1.02 (53)	0.41 (35) 0.53 (100) 0.66 (100) 0.74 (88) 1.15 (13)
Iodine-131	8.06 d	Fission product $^{130}\text{Te}(n,\gamma)^{131}\text{Te} \xrightarrow{(25\text{ m})} ^{131}\text{I}$	$\beta^-$ , $\gamma$ , $e^-$	0.33 (7) 0.61 (90) Others	0.28 (6) 0.36 (82) 0.64 (7) Others
Iodine-132	2.3 h	Fission product $^{132}\text{Te} \xrightarrow{(78\text{ h})} ^{132}\text{I}$	$\beta^-$ , $\gamma$	0.72 (14) 1.16 (19) 1.45 (11) 1.60 (13) 2.12 (20) Others	0.52 (16) 0.65–0.67 (112) 0.77 (76) 0.95 (18) Others
Iodine-133 [Note: contains $^{133m}\text{Xe}$ and $^{133}\text{Xe}$ daughters]	20.9 h	Fission product	$\beta^-$ , $\gamma$	1.23 (86) Others	0.53 (90) 0.86–0.87 (7)
Iridium-192	74 d	$^{191}\text{Ir}(n,\gamma)^{192}\text{Ir}$	$\beta^-$ (96%), EC (4%), $\gamma$	0.24 (8) 0.54 (42) 0.67 (46)	0.30–0.32 (~140) 0.47 (49) 0.59–0.61 (20) Others
Iridium-194	19.4 h	$^{193}\text{Ir}(n,\gamma)^{194}\text{Ir}$	$\beta^-$ , $\gamma$	2.24 (88) Others	0.29 (2) 0.33 (11) Others
Iron-52 [Note: contains $^{52m}\text{Mn}$ and $^{52}\text{Mn}$ daughters]	8.3 h	$^{50}\text{Cr}(\alpha,2n)^{52}\text{Fe}$	$\beta^+$ (56%), EC (44%), $\gamma$	0.80 (56)	$\gamma^\pm$ (112) 0.17 (100) Mn x rays

<sup>a</sup>Abundances are given in parentheses.



Isotope	Half-Life	Production Method(s)	Decay Mode(s)	Decay Energies (MeV) and Abundances (%) <sup>a</sup>	
				Particles	Photons
Manganese-52	5.7 d	$^{52}\text{Cr}(p,n)^{52}\text{Mn}$	EC (73%), $\beta^+$ (27%), $\gamma$	0.58 (27)	$\gamma^\pm$ (54) 0.74 (82) 0.94 (92) 1.43 (100) Cr x rays Others
Manganese-54	313 d	$^{54}\text{Cr}(p,n)^{54}\text{Mn}$ $^{54}\text{Fe}(n,p)^{54}\text{Mn}$	EC, $\gamma$		0.835 (100) Cr x rays
Manganese-56	2.58 h	$^{55}\text{Mn}(n,\gamma)^{56}\text{Mn}$	$\beta^-$ , $\gamma$	0.73 (16) 1.04 (~30) 2.84 (~53)	0.85 (99) 1.81 (29) 2.11 (15)
Mercury-197m– Mercury-197	$^{197m}\text{Hg}$ , 24 h; $^{197}\text{Hg}$ , 64 h	$^{196}\text{Hg}(n,\gamma)^{197m}\text{Hg} \xrightarrow{(24\text{ h})} ^{197}\text{Hg}$	IT (~95%), EC (~5%), $\gamma$ , $e^-$ ; EC, $\gamma$ , $e^-$		$^{197m}\text{Hg}$ : 0.134 (~42) Hg x rays Others $^{197}\text{Hg}$ : 0.077 (~23) Au x rays
Mercury-203	46.5 d	$^{202}\text{Hg}(n,\gamma)^{203}\text{Hg}$	$\beta^-$ , $\gamma$	0.21	0.279 (82) Tl x rays
Molybdenum-99– Technetium-99m	$^{99}\text{Mo}$ , 66.3 h; $^{99m}\text{Tc}$ , 6.02 h	$^{98}\text{Mo}(n,\gamma)^{99}\text{Mo} \xrightarrow{(66.3\text{ h})} ^{99m}\text{Tc}$ Fission product	$\beta^-$ , $\gamma$ ; IT, $\gamma$	$^{99}\text{Mo}$ : 0.45 (18) 1.23 (80) Others	$^{99}\text{Mo}$ : 0.18 (7) 0.74 (13) 0.78 (4) Others $^{99m}\text{Tc}$ : 0.14 (90)
Neodymium-147 [Note: contains $^{147}\text{Pm}$ daughter]	11.1 d	Fission product	$\beta^-$ , $\gamma$ , $e^-$	0.37 (~20) 0.81 (~77) Others	0.091 (27) 0.53 (13) Pm x rays Others
Neodymium-149 [Note: contains $^{149}\text{Pm}$ daughter]	1.8 h	$^{148}\text{Nd}(n,\gamma)^{149}\text{Nd}$	$\beta^-$ , $\gamma$ , $e^-$	1.02 (~18) 1.13 (~20) 1.40 (~19) 1.46 (~25) 1.56 (~9) Others	0.11 (18) 0.21 (27) 0.27 (18) Pm x rays Others

<sup>a</sup>Abundances are given in parentheses.

Isotope	Half-Life	Production Method(s)	Decay Mode(s)	Decay Energies (MeV) and Abundances (%) <sup>a</sup>	
				Particles	Photons
Neptunium-237 [Note: contains <sup>233</sup> Pa daughter]	2.14 × 10 <sup>6</sup> y	<sup>235</sup> U(n,γ) <sup>236</sup> U(n,γ) <sup>237</sup> U $\beta^- / (6.75 \text{ d})$ <sup>237</sup> Np  <sup>238</sup> U(n,2n) <sup>237</sup> U $\xrightarrow{(6.75 \text{ d})} \beta^-$ <sup>237</sup> Np	α, γ, e <sup>-</sup>	4.76 (33) 4.79 (50) Others	0.030 (14) 0.086 (14) Pa L x rays Others
Nickel-59	8 × 10 <sup>4</sup> y	<sup>58</sup> Ni(n,γ) <sup>59</sup> Ni <sup>59</sup> Co(d,2n) <sup>59</sup> Ni <sup>59</sup> Co(p,m) <sup>59</sup> Ni	EC		Co x rays
Nickel-63	92 y	<sup>62</sup> Ni(n,γ) <sup>63</sup> Ni, using target enriched in <sup>62</sup> Ni	β <sup>-</sup>	0.067	
Nickel-65	2.56 h	<sup>64</sup> Ni(n,γ) <sup>65</sup> Ni	β <sup>-</sup> , γ	0.62 (29) 1.0 (11) 2.1 (58)	0.37 (5) 1.11 (16) 1.48 (25)
Nickel-66–Copper-66	<sup>66</sup> Ni, 55 h; <sup>66</sup> Cu, 5 m	<sup>64</sup> Ni(n,γ) <sup>65</sup> Ni(n,γ) <sup>66</sup> Ni $\xrightarrow{(55 \text{ h})} \beta^-$ <sup>66</sup> Cu	β <sup>-</sup> ; β <sup>-</sup> , γ	<sup>66</sup> Ni: 0.20 <sup>66</sup> Cu: 1.59 (9) 2.63 (91)	<sup>66</sup> Cu: 1.04 (9)
Niobium-94	2.0 × 10 <sup>4</sup> y	<sup>93</sup> Nb(n,γ) <sup>94</sup> Nb	β <sup>-</sup> , γ	0.5	0.70 (100) 0.87 (100)
Niobium-95	35 d	Fission product <sup>95</sup> Zr $\xrightarrow{(65 \text{ d})} \beta^-$ <sup>95</sup> Nb	β <sup>-</sup> , γ	0.16 (100)	0.77 (100)
Osmium-185	94 d	<sup>184</sup> Os(n,γ) <sup>185</sup> Os	EC, γ, e <sup>-</sup>		0.65 (80) 0.87–0.88 (14) Re x rays Others
Osmium-191m [Note: contains <sup>191</sup> Os daughter]	13 h	<sup>190</sup> Os(n,γ) <sup>191m</sup> Os	IT, e <sup>-</sup>		Os L x rays
Osmium-191	15 d	<sup>190</sup> Os(n,γ) <sup>191m</sup> Os $\xrightarrow{(13 \text{ h})} \text{IT}$ <sup>191</sup> Os	β <sup>-</sup> , γ, e <sup>-</sup>	0.14	0.13 (~22) Ir x rays
Osmium-193	32 h	<sup>192</sup> Os(n,γ) <sup>193</sup> Os	β <sup>-</sup> , γ, e <sup>-</sup>	1.13 (~70) Others	0.46 (4) Ir x rays Others

<sup>a</sup>Abundances are given in parentheses.

Isotope	Half-Life	Production Method(s)	Decay Mode(s)	Decay Energies (MeV) and Abundances (%) <sup>a</sup>	
				Particles	Photons
Palladium-103 [Note: contains <sup>103m</sup> Rh daughter]	17 d	<sup>102</sup> Pd( <i>n,γ</i> ) <sup>103</sup> Pd <sup>103</sup> Rh( <i>p,n</i> ) <sup>103</sup> Pd	EC, e <sup>-</sup>		Rh x rays
Palladium-109– Silver-109 <sup>m</sup>	<sup>109</sup> Pd, 13.6 h; <sup>109m</sup> Ag, 40 s	<sup>108</sup> Pd( <i>n,γ</i> ) <sup>109</sup> Pd $\xrightarrow[(13.6 \text{ h})]{\beta^-}$ <sup>109m</sup> Ag	β <sup>-</sup> ; IT, e <sup>-</sup>	<sup>109</sup> Pd: 1.02	<sup>109m</sup> Ag: 0.088 (4) Ag x rays
Phosphorus-32	14.3 d	<sup>32</sup> S( <i>n,p</i> ) <sup>32</sup> P <sup>35</sup> Cl( <i>n,α</i> ) <sup>32</sup> P <sup>31</sup> P( <i>n,γ</i> ) <sup>32</sup> P	β <sup>-</sup>	1.71	
Phosphorus-33	25 d	<sup>36</sup> Cl( <i>n,α</i> ) <sup>33</sup> P <sup>33</sup> S( <i>n,p</i> ) <sup>33</sup> P, using target enriched in stable <sup>33</sup> S	β <sup>-</sup>	0.25	
Platinum-193 <sup>m</sup>	4.3 d	<sup>192</sup> Pt( <i>n,γ</i> ) <sup>193m</sup> Pt	IT, e <sup>-</sup>		Pt x rays
Platinum-197	20 h	<sup>196</sup> Pt( <i>n,γ</i> ) <sup>197</sup> Pt	β <sup>-</sup> , γ, e <sup>-</sup>	0.48 (~10) 0.67 (~90)	Pt x rays Au x rays Others
Plutonium-237	45.6 d	<sup>235</sup> U( <i>α,2n</i> ) <sup>237</sup> Pu	EC, γ, e <sup>-</sup>		0.060 (5) Np x rays
Plutonium-238	87.6 y	<sup>241</sup> Am( <i>n,γ</i> ) <sup>242</sup> Am $\xrightarrow[(16 \text{ h})]{\beta^-}$ <sup>242</sup> Cm $\alpha \downarrow (163 \text{ d})$ <sup>238</sup> Pu	α, e <sup>-</sup>	5.46 (28) 5.50 (72)	0.099 (8 × 10 <sup>-3</sup> ) U L x rays
Plutonium-239	2.44 × 10 <sup>4</sup> y	<sup>237</sup> Np( <i>n,γ</i> ) <sup>238</sup> Np $\xrightarrow[(2.1 \text{ d})]{\beta^-}$ <sup>238</sup> Pu <sup>238</sup> U( <i>n,γ</i> ) <sup>239</sup> U $\xrightarrow[(23.5 \text{ m})]{\beta^-}$ <sup>239</sup> Np $\beta^- \downarrow (2.35 \text{ d})$ <sup>239</sup> Pu	α, e <sup>-</sup>	5.16 (88) 5.11 (11)	0.38 (7 × 10 <sup>-3</sup> ) U x rays
Poisonium-208	2.9 y	<sup>209</sup> Bi( <i>p,2n</i> ) <sup>208</sup> Po	α	5.11	
Poisonium-210	138.4 d	<sup>209</sup> Bi( <i>n,γ</i> ) <sup>210</sup> Bi $\xrightarrow[(5 \text{ d})]{\beta^-}$ <sup>210</sup> Po	α	5.30	
Potassium-40	1.28 × 10 <sup>9</sup> y	Naturally occurring; abundance 0.012% <sup>39</sup> K( <i>n,γ</i> ) <sup>40</sup> K	β <sup>-</sup> (89%), EC (11%), γ	1.31 (89)	1.46 (11) Ar x rays
Potassium-42	12.4 h	<sup>41</sup> K( <i>n,γ</i> ) <sup>42</sup> K	β <sup>-</sup> , γ	2.00 (18) 3.52 (82)	1.52 (18)

<sup>a</sup>Abundances are given in parentheses.

Isotope	Half-Life	Production Method(s)	Decay Modes(s)	Decay Energies (MeV) and Abundances (%) <sup>a</sup>	
				Particles	Photons
Potassium-43	22 h	$^{40}\text{Ar}(\alpha,p)^{43}\text{K}$ $^{43}\text{Ca}(n,p)^{43}\text{K}$	$\beta^-$ , $\gamma$	0.83 (~93) Others	0.37 (86) 0.40 (11) 0.59 (13) 0.62 (81) Others
Praseodymium-142	19.2 h	$^{141}\text{Pr}(n,\gamma)^{142}\text{Pr}$	$\beta^-$ , $\gamma$	0.58 (4) 2.15 (96)	1.57 (4)
Praseodymium-143	13.6 d	Fission product	$\beta^-$	0.93	0.07 (~3)
Promethium-145	18 y	$^{144}\text{Sm}(n,\gamma)^{145}\text{Sm} \xrightarrow{(340\text{ d})} ^{145}\text{Pm}$	EC, $\gamma$ , $e^-$		Nd x rays
Promethium-146	5.5 y	$^{146}\text{Nd}(p,n)^{146}\text{Pm}$	EC (~67%), $\beta^-$ (~33%), $\gamma$	0.78 (~33)	0.45 (~67) 0.74–0.75 (~55) Nd x rays
Promethium-147	2.62 y	Fission product	$\beta^-$	0.22	0.12 (0.004)
Promethium-149	53 h	$^{148}\text{Nd}(n,\gamma)^{149}\text{Nd} \xrightarrow{(1.8\text{ h})} ^{149}\text{Pm}$	$\beta^-$ , $\gamma$	0.78 (3) 1.07 (97)	0.29 (2)
Promethium-151	28 h	$^{150}\text{Nd}(n,\gamma)^{151}\text{Nd} \xrightarrow{(12\text{ m})} ^{151}\text{Pm}$	$\beta^-$ , $\gamma$ , $e^-$	0.85 (40) 1.19 (10) Others	0.17 (18) 0.34 (21) Sm x rays Others
Protactinium-231	$3.4 \times 10^4$ y	Natural decay of $^{235}\text{U}$ chain	$\alpha$ , $\gamma$ , $e^-$	4.94 (22) 5.00 (24) 5.02 (23) Others	0.027 (6) 0.29 (6) Ac x rays
Protactinium-233	27.0 d	$^{232}\text{Th}(n,\gamma)^{233}\text{Th} \xrightarrow{(22\text{ m})} ^{233}\text{Pa}$	$\beta^-$ , $\gamma$ , $e^-$	0.15 0.26 0.58 Others	0.29–0.33 (~50) U x rays Others
Protactinium-234	6.7 h	Natural decay of $^{238}\text{U}$ chain	$\beta^-$ , $\gamma$ , $e^-$	Complex	0.10 (~50) 0.90 (~70) U x rays Others

<sup>a</sup>Abundances are given in parentheses.

Isotope	Half-Life	Production Method(s)	Decay Mode(s)	Decay Energies (MeV) and Abundances (%) <sup>a</sup>	
				Particles	Photons
Radium-224 [Note: contains many daughters]	87.4 h	Natural decay of <sup>232</sup> Th chain	α, γ	5.45 (5) 5.68 (95)	0.24 (4)
Radium-226 [Note: contains many daughters]	1600 y	Natural decay of <sup>238</sup> U chain	α, γ	4.59 (6) 4.78 (94)	0.19 (4)
Radium-228 [Note: contains <sup>228</sup> Ac daughter and others]	5.7 y	Natural decay of <sup>232</sup> Th chain	β <sup>-</sup>	0.05	
Radon-222	3.82 d	Natural decay of <sup>238</sup> U chain	α	5.49	
Rhenium-183	70 d	<sup>184</sup> W(p,2n) <sup>183</sup> Re	EC, γ, e <sup>-</sup>		0.05 (~11) 0.16 (~20) W x rays Others
Rhenium-186	90 h	<sup>185</sup> Re(n,γ) <sup>186</sup> Re	β <sup>-</sup> (94%), EC (6%), γ	0.93 (24) 1.07 (70)	0.137 (~10) Os x rays W x rays Others
Rhenium-188	17 h	<sup>187</sup> Re(n,γ) <sup>188</sup> Re <sup>186</sup> W(n,γ) <sup>187</sup> W(n,γ) <sup>188</sup> W $\xrightarrow[69 \text{ d}]{\beta^-}$ <sup>188</sup> Re	β <sup>-</sup> , γ, e <sup>-</sup>	1.96 (~24) 2.12 (~74) Others	0.155 (13) 0.48 (1.0) 0.63 (1.2) Os x rays Others
Rhodium-102	206 d	<sup>102</sup> Ru(p,n) <sup>102</sup> Rh	EC (~70%), β <sup>-</sup> (~17%), β <sup>+</sup> (~13%), γ	β <sup>-</sup> : 1.15 (~17) β <sup>+</sup> : 0.81 (~4) 1.28 (~9)	γ <sup>±</sup> (~26) 0.48 (~55) Ru x rays Others
Rhodium-103m	57 m	<sup>103</sup> Rh(n,n') <sup>103m</sup> Rh <sup>103</sup> Ru $\xrightarrow[39.7 \text{ d}]{\beta^-}$ <sup>103m</sup> Rh <sup>103</sup> Pd $\xrightarrow[17 \text{ d}]{EC}$ <sup>103m</sup> Rh	IT, e <sup>-</sup>		0.020 (x ray) (8) 0.040 (0.06)

<sup>a</sup>Abundances are given in parentheses.

Isotope	Half-Life	Production Method(s)	Decay Modes(s)	Decay Energies (MeV) and Abundances (%) <sup>a</sup>	
				Particles	Photons
Rhodium-105	36 h	$^{104}\text{Ru}(n,\gamma)^{105}\text{Ru} \xrightarrow{(4.4\text{ h})} ^{105}\text{Rh}$	$\beta^-$ , $\gamma$	0.25 (25) 0.56 (75)	0.31–0.32 (24)
Rubidium-83	83 d	$^{81}\text{Br}(\alpha,2n)^{83}\text{Rb}$	EC, $\gamma$ , $e^-$		0.52–0.55 (93)
Rubidium-84	33 d	$^{84}\text{Sr}(n,p)^{84}\text{Rb}$ $^{84}\text{Kr}(p,n)^{84}\text{Rb}$	$\beta^+$ (21%), $\beta^-$ (3%), EC (76%), $\gamma$	$\beta^+$ : 0.80 (11) 1.65 (10) $\beta^-$ : 0.90 (3)	Kr x rays $\gamma^\pm$ (42) 0.88 (73) Kr x rays Others
Rubidium-86	18.7 d	$^{85}\text{Rb}(n,\gamma)^{86}\text{Rb}$	$\beta^-$ , $\gamma$	0.69 (9) 1.77 (91)	1.08 (9)
Ruthenium-97	69.6 h	$^{96}\text{Ru}(n,\gamma)^{97}\text{Ru}$	EC, $\gamma$ , $e^-$		0.22 (92) 0.32 (8) Tc x rays
Ruthenium-103 [Note: contains $^{103m}\text{Rh}$ daughter]	39.7 d	Fission product $^{102}\text{Ru}(n,\gamma)^{103}\text{Ru}$	$\beta^-$ , $\gamma$	0.10 (7) 0.21 (89) 0.71 (3)	0.50 (88) 0.61 (6)
Ruthenium-106– Rhodium-106	$^{106}\text{Ru}$ , 1.01 y; $^{106}\text{Rh}$ , 30 s	Fission product $^{106}\text{Ru} \xrightarrow{(1.01\text{ y})} ^{106}\text{Rh}$	$\beta^-$ ; $\beta^-$ , $\gamma$	$^{106}\text{Ru}$ : 0.039 $^{106}\text{Rh}$ : 2.0 (2) 2.4 (11) 3.0 (8) 3.54 (78)	$^{106}\text{Rh}$ : 0.51 (21) 0.62 (11) Others
Samarium-151	~90 y	Fission product $^{150}\text{Sm}(n,\gamma)^{151}\text{Sm}$	$\beta^-$ , $e^-$	0.076 (~98)	0.022 (~0.06)
Samarium-153	46.8 h	$^{152}\text{Sm}(n,\gamma)^{153}\text{Sm}$	$\beta^-$ , $\gamma$	0.64 (33) 0.70 (46) 0.80 (20)	0.070 (5) 0.103 (28) Others
Scandium-44	3.9 h	$^{44}\text{Ti} \xrightarrow{(47\text{ y})} ^{44}\text{Sc}$ (EC)	$\beta^+$ (94%), EC (6%), $\gamma$	1.47 (94)	1.16 (100) $\gamma^\pm$ (188)
Scandium-46	84 d	$^{45}\text{Sc}(n,\gamma)^{46}\text{Sc}$	$\beta^-$ , $\gamma$	0.36	0.89 (100) 1.12 (100)

<sup>a</sup>Abundances are given in parentheses.

Isotope	Half-Life	Production Method(s)	Decay Mode(s)	Decay Energies (MeV) and Abundances (%) <sup>a</sup>	
				Particles	Photons
Selenium-75	120 d	$^{74}\text{Se}(n,\gamma)^{75}\text{Se}$	EC, $\gamma$ , $e^-$		0.12 (16) 0.14 (54) 0.26–0.28 (84) 0.40 (13) As x rays Others
Silicon-31	2.62 h	$^{30}\text{Si}(n,\gamma)^{31}\text{Si}$ $^{31}\text{P}(n,p)^{31}\text{Si}$	$\beta^-$	1.48	
Silver-105	40 d	$^{106}\text{Pd}(p,2n)^{105}\text{Ag}$	EC, $\gamma$ , $e^-$		0.28 (32) 0.32–0.34 (42) Pd x rays Others
Silver-110m– Silver-110	$^{110m}\text{Ag}$ , 253 d; $^{110}\text{Ag}$ , 24 s	$^{109}\text{Ag}(n,\gamma)^{110m}\text{Ag} \xrightarrow[\text{(253 d)}]{\text{IT}} ^{110}\text{Ag}$	$\beta^-$ (98%), $\gamma$ , IT (2%); $\beta^-, \gamma$	$^{110m}\text{Ag}$ : 0.085 (~65) 0.53 (~33) $^{110}\text{Ag}$ : 2.87 (~2)	0.66 (96) 0.68 (19) 0.71 (16) 0.76 (23) 0.88 (76) 0.94 (35) 1.38 (27) 1.50 (14) Others
Silver-111	7.5 d	$^{110}\text{Pd}(n,\gamma)^{111}\text{Pd} \xrightarrow[\text{(22 m)}]{\beta^-} ^{111}\text{Ag}$	$\beta^-, \gamma$	0.7 (6) 0.8 (1) 1.05 (93)	0.25 (1) 0.34 (6)
Sodium-22	2.60 y	$^{25}\text{Mg}(p,\alpha)^{22}\text{Na}$ $^{26}\text{Mg}(p,\alpha n)^{22}\text{Na}$	$\beta^+$ (90%), EC (10%), $\gamma$	0.54 (90)	$\gamma^\pm$ (180) 1.27 (100)
Sodium-24	15.0 h	$^{23}\text{Na}(n,\gamma)^{24}\text{Na}$ $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$	$\beta^-, \gamma$	1.39 (100)	1.37 (100) 2.75 (100)
Strontium-85	65 d	$^{84}\text{Sr}(n,\gamma)^{85}\text{Sr}$ , using target enriched in $^{84}\text{Sr}$ $^{85}\text{Rb}(p,n)^{85}\text{Sr}$	EC, $\gamma$		0.51 (99) Rb x rays
Strontium-87m	2.8 h	$^{87}\text{Sr}(p,n)^{87m}\text{Y} \xrightarrow[\text{(80 h)}]{\text{EC}} ^{87m}\text{Sr}$	IT, $e^-$		0.39 (82) Sr x rays

<sup>a</sup>Abundances are given in parentheses.

Isotope	Half-Life	Production Method(s)	Decay Mode(s)	Decay Energies (MeV) and Abundances (%) <sup>a</sup>	
				Particles	Photons
Strontium-89	51 d	Fission product	$\beta^-$	1.46	
Strontium-90– Yttrium-90	$^{90}\text{Sr}$ , 28.5 y; $^{90}\text{Y}$ , 64.0 h	Fission product $^{90}\text{Sr} \xrightarrow{(28.5\text{ y})} ^{90}\text{Y}$	$\beta^-; \beta^-$	$^{90}\text{Sr}$ : 0.54 $^{90}\text{Y}$ : 2.28	
Sulfur-35	88 d	$^{35}\text{Cl}(n,p)^{35}\text{S}$ $^{34}\text{S}(n,\gamma)^{35}\text{S}$	$\beta^-$	0.167	
Tantalum-179	~1.6 y	$^{181}\text{Ta}(p,3n)^{179}\text{W} \xrightarrow{(30\text{ m})} ^{179}\text{Ta}$ $^{179}\text{Hf}(p,n)^{179}\text{Ta}$	EC		Hf x rays
Tantalum-182	115 d	$^{181}\text{Ta}(n,\gamma)^{182}\text{Ta}$	$\beta^-, \gamma, e^-$	0.25 (~30) 0.43 (~22) 0.52 (~42) Others	0.068 (42) 0.100 (14) 0.15 (7) 0.22 (8) 1.12 (34) 1.19 (16) 1.22–1.23 (40) Others
Technetium-97	$2.6 \times 10^6$ y	$^{96}\text{Ru}(n,\gamma)^{97}\text{Ru} \xrightarrow{(2.9\text{ d})} ^{97}\text{Tc}$	EC		Mo x rays
Technetium-99	$2.1 \times 10^5$ y	Fission product $^{99m}\text{Tc} \xrightarrow{(6.02\text{ h})} ^{99}\text{Tc}$	$\beta^-$	0.29	
Tellurium-121m– Tellurium-121	$^{121m}\text{Te}$ , 154 d; $^{121}\text{Te}$ , 17 d	$^{120}\text{Te}(n,\gamma)^{121m}\text{Te} \xrightarrow{(154\text{ d})} ^{121}\text{Te}$	IT (90%), EC (10%), $\gamma, e^-; \text{EC}, \gamma$		$^{121m}\text{Te}$ : 0.21 (82) Te x rays Sb x rays $^{121}\text{Te}$ : 0.51 (18) 0.57 (80) Sb x rays
Tellurium-123m	120 d	$^{122}\text{Te}(n,\gamma)^{123m}\text{Te}$	IT, $\gamma, e^-$		0.16 (84) Te x rays
Tellurium-125m	58 d	$^{125}\text{Sn} \xrightarrow{(9.4\text{ d})} ^{125}\text{Sb} \xrightarrow{(2.7\text{ y})} ^{125m}\text{Te}$ $^{124}\text{Te}(n,\gamma)^{125m}\text{Te}$	IT, $e^-$		0.035 (7) Te x rays

<sup>a</sup>Abundances are given in parentheses.

Isotope	Half-Life	Production Method(s)	Decay Mode(s)	Decay Energies (MeV) and Abundances (%) <sup>a</sup>	
				Particles	Photons
Tellurium-127m- Tellurium-127	<sup>127m</sup> Te, 109 d; <sup>127</sup> Te, 9.3 h	<sup>126</sup> Te(n,γ) <sup>127m</sup> Te $\xrightarrow{(109\text{ d})}$ <sup>127</sup> Te	IT, e <sup>-</sup> ; β <sup>-</sup>	<sup>127</sup> Te: 0.70	<sup>127m</sup> Te: Te x rays
		<sup>126</sup> Te(n,γ) <sup>127</sup> Te			
Tellurium-129m- Tellurium-129	<sup>129m</sup> Te, 34 d; <sup>129</sup> Te, 69 m	<sup>128</sup> Te(n,γ) <sup>129m</sup> Te $\xrightarrow{(34\text{ d})}$ <sup>129</sup> Te	IT (66%), β <sup>-</sup> (34%), γ, e <sup>-</sup> ; β <sup>-</sup> , γ, e <sup>-</sup>	<sup>129m</sup> Te: 0.90 (6) 1.59 (28)	0.69 (6) Te x rays
		<sup>128</sup> Te(n,γ) <sup>129</sup> Te		<sup>129</sup> Te: 0.99 (16) 1.45 (80)	0.027 (19) 0.46 (15) I x rays Others
Tellurium-132 [Note: contains <sup>132</sup> I daughter]	78 h	Fission product	β <sup>-</sup> , γ, e <sup>-</sup>	0.22	0.053 (17) 0.23 (90) I x rays
		<sup>159</sup> Tb(n,γ) <sup>160</sup> Tb	β <sup>-</sup> , γ, e <sup>-</sup>	0.57 (44) 0.87 (29) Others	0.087 (13) 0.30 (29) 0.88 (31) Dy x rays Others
Terbium-160	72.4 d				
		<sup>160</sup> Gd(n,γ) <sup>161</sup> Gd $\xrightarrow{(3.7\text{ m})}$ <sup>161</sup> Tb	β <sup>-</sup> , γ, e <sup>-</sup>	0.45 (26) 0.51 (64) 0.58 (10)	0.026 (21) 0.049 (19) Dy x rays Others
Terbium-161	6.9 d				
		<sup>203</sup> Tl(n,γ) <sup>204</sup> Tl	β <sup>-</sup> (~98%), EC (~2%)	0.76 (~98)	Hg x rays
Thallium-204	3.8 y	Natural decay of <sup>232</sup> Th chain	α, e <sup>-</sup>	5.34 (28) 5.43 (71)	Ra L x rays
Thorium-228 [Note: contains many daughters]	1.91 y	Natural decay of <sup>238</sup> U chain	α, e <sup>-</sup>	4.62 (24) 4.68 (76)	Ra L x rays
Thorium-230	8 × 10 <sup>4</sup> y	Naturally occurring	α, e <sup>-</sup>	3.95 (24) 4.01 (76)	Ra L x rays
Thorium-232	1.39 × 10 <sup>10</sup> y	Naturally occurring			

<sup>a</sup>Abundances are given in parentheses.

Isotope	Half-Life	Production Method(s)	Decay Mode(s)	Decay Energies (MeV) and Abundances (%) <sup>a</sup>	
				Particles	Photons
Thorium-234– Protactinium-234 <sub>m</sub>	<sup>234</sup> Th, 24 d; <sup>234m</sup> Pa, 1.2 m	Natural decay of <sup>238</sup> U chain; $^{234}\text{Th} \xrightarrow[\text{(24 d)}]{\beta^-} ^{234m}\text{Pa}$	$\beta^-, \gamma, e^-; \beta^-, \gamma$	<sup>234</sup> Th: 0.19 (~80) 0.10 (~20)  <sup>234m</sup> Pa: 2.29 (98)	<sup>234</sup> Th: 0.063 (~4) 0.093 (~4) Pa L x rays Others <sup>234m</sup> Pa: 0.76 (~0.3) 1.00 (~0.6) U L x rays Others
Thulium-170	129 d	<sup>169</sup> Tm( <i>n, γ</i> ) <sup>170</sup> Tm	$\beta^-, e^-, \gamma$	0.97 (76)	0.084 (3.3)
Thulium-171	700 d	<sup>170</sup> Tm( <i>n, γ</i> ) <sup>171</sup> Tm <sup>170</sup> Er( <i>n, γ</i> ) <sup>171</sup> Er $\xrightarrow[\text{(7.5 h)}]{\text{EC}}$ <sup>171</sup> Tm	$\beta^-, \gamma, e^-$	0.88 (24) 0.097 (~98)	Yb x rays 0.067 (~0.2) Yb x rays
Tin-113– Indium-113 <sub>m</sub>	<sup>113</sup> Sn, 115 d; <sup>113m</sup> In, 1.7 h	<sup>112</sup> Sn( <i>n, γ</i> ) <sup>113</sup> Sn $\xrightarrow[\text{(115 d)}]{\text{EC}}$ <sup>113m</sup> In	EC, γ; IT, e <sup>-</sup>		<sup>113</sup> Sn: 0.26 (2) In x rays <sup>113m</sup> In: 0.39 (66) In x rays
Tin-119 <sub>m</sub>	250 d	<sup>118</sup> Sn( <i>n, γ</i> ) <sup>119m</sup> Sn	IT, γ, e <sup>-</sup>		0.024 (~14) Sn x rays
Tin-121	27 h	<sup>120</sup> Sn( <i>n, γ</i> ) <sup>121</sup> Sn	$\beta^-$	0.38	
Titanium-44 [Note: contains <sup>44</sup> Sc daughter]	47 y	<sup>45</sup> Sc( <i>p, 2n</i> ) <sup>44</sup> Ti	EC, γ, e <sup>-</sup>		0.068 (~90) 0.078 (~98) Sc x rays
Tungstén-181	122 d	<sup>180</sup> W( <i>n, γ</i> ) <sup>181</sup> W <sup>181</sup> Ta( <i>p, n</i> ) <sup>181</sup> W	EC, e <sup>-</sup>		Ta x rays
Tungsten-185	75 d	<sup>184</sup> W( <i>n, γ</i> ) <sup>185</sup> W	$\beta^-$	0.43	
Tungsten-187	24 h	<sup>186</sup> W( <i>n, γ</i> ) <sup>187</sup> W	$\beta^-, e^-, \gamma$	0.63 (59) 1.33 (20) Others	0.072 (12) 0.13 (10) 0.48 (24) 0.69 (28) Re x rays Others

<sup>a</sup>Abundances are given in parentheses.

Isotope	Half-Life	Production Method(s)	Decay Mode(s)	Decay Energies (MeV) and Abundances (%) <sup>a</sup>	
				Particles	Photons
Tungsten-188 [Note: contains <sup>188</sup> Re daughter]	69 d	<sup>186</sup> W(n,γ) <sup>187</sup> W(n,γ) <sup>188</sup> W	β <sup>-</sup>	0.35	
Uranium-232	71.7 y	<sup>231</sup> Pa(n,γ) <sup>232</sup> Pa $\xrightarrow[1.3 \text{ d}]{\beta^-}$ <sup>232</sup> U	α, e <sup>-</sup>	5.27 (32) 5.32 (68)	0.058 (0.2) Th L x rays Others
Uranium-233	1.62 × 10 <sup>5</sup> y	<sup>232</sup> Th(n,γ) <sup>233</sup> Th $\xrightarrow[22 \text{ m}]{\beta^-}$ <sup>233</sup> Pa $\xrightarrow[27 \text{ d}]{\beta^-}$ <sup>233</sup> U	α, e <sup>-</sup>	4.78 (15) 4.82 (83)	Th x rays
Uranium-235 [Note: contains <sup>231</sup> Th daughter]	7.13 × 10 <sup>8</sup> y	Naturally occurring	α, γ, e <sup>-</sup>	4.39 (60) 4.36 (19) Others	0.185 (55) Th x rays Others
Uranium-238 [Note: contains <sup>234</sup> Th daughter]	4.51 × 10 <sup>9</sup> y	Naturally occurring	α, e <sup>-</sup>	4.15 (25) 4.20 (75)	Th L x rays
Vanadium-48	16.1 d	<sup>48</sup> Ti(p,n) <sup>48</sup> V	β <sup>+</sup> (~50%), EC (~50%), γ	0.70 (~50)	γ <sup>±</sup> (100) 0.98 (100) 1.31 (97) Ti x rays Others
Vanadium-49	330 d	<sup>52</sup> Cr(p,α) <sup>49</sup> V	EC		Ti x rays
Xenon-129m	8 d	<sup>127</sup> I(n,γ) <sup>128</sup> I $\xrightarrow[25 \text{ m}]{\beta^-}$ <sup>128</sup> Xe(n,γ) <sup>129m</sup> Xe	IT, e <sup>-</sup>		0.040 (7) 0.197 (~5) Xe x rays
Xenon-131m	12 d	<sup>131</sup> I $\xrightarrow[8.06 \text{ d}]{\beta^-}$ <sup>131m</sup> Xe <sup>129</sup> I(n,γ) <sup>130</sup> I $\xrightarrow[12.3 \text{ h}]{\beta^-}$ <sup>130</sup> Xe(n,γ) <sup>131m</sup> Xe	IT, e <sup>-</sup>		0.164 (2) Xe x rays
Xenon-133	5.3 d	Fission product	β <sup>-</sup> , γ	0.34	0.081 (36)

<sup>a</sup>Abundances are given in parentheses.

Isotope	Half-Life	Production Method(s)	Decay Mode(s)	Decay Energies (MeV) and Abundances (%) <sup>a</sup>	
				Particles	Photons
Ytterbium-169	31 d	$^{168}\text{Yb}(n,\gamma)^{169}\text{Yb}$	EC, $\gamma$ , $e^-$		0.063 (45) 0.11 (18) 0.18 (22) 0.20 (34) Tm x rays Others
Ytterbium-175	4.2 d	$^{174}\text{Yb}(n,\gamma)^{175}\text{Yb}$	$\beta^-$ , $\gamma$ , $e^-$	0.07 (11) 0.47 (87)	0.40 (6) Lu x rays Others
Yttrium-87 [Note: contains $^{87m}\text{Sr}$ daughter]	80 h	$^{87}\text{Sr}(p,n)^{87}\text{Y}$	EC, $\gamma$		0.48 (92) Sr x rays
Yttrium-88	107 d	$^{88}\text{Sr}(p,n)^{88}\text{Y}$	EC, $\gamma$		0.90 (94) 1.84 (99) Sr x rays
Yttrium-90	64.0 h	Fission product $^{90}\text{Sr} \xrightarrow{(28.5\text{ y})} ^{90}\text{Y}$	$\beta^-$	2.28	
Yttrium-91	59 d	Fission product	$\beta^-$ , $\gamma$	0.33 (0.3) 1.54 (99.7)	1.21 (0.3)
Zinc-65	244 d	$^{64}\text{Zn}(n,\gamma)^{65}\text{Zn}$ $^{65}\text{Cu}(p,n)^{65}\text{Zn}$	$\beta^+$ (1.5%), EC (98%), $\gamma$	0.33 (1.5)	1.12 (50) Cu x rays
Zinc-69m - Zinc-69	$^{69m}\text{Zn}$ , 14 h; $^{69}\text{Zn}$ , 55 m	$^{68}\text{Zn}(n,\gamma)^{69m}\text{Zn} \xrightarrow{(14\text{ h})} ^{69}\text{Zn}$ $^{69}\text{Ga}(n,p)^{69m}\text{Zn} \xrightarrow{(14\text{ h})} ^{69}\text{Zn}$	IT, $e^-$ ; $\beta^-$	$^{69}\text{Zn}$ : 0.90	$^{69m}\text{Zn}$ : 0.44 (95)
Zirconium-95 - Niobium-95	$^{95}\text{Zr}$ , 65 d; $^{95}\text{Nb}$ , 35 d	Fission product $^{95}\text{Zr} \xrightarrow{(65\text{ d})} ^{95}\text{Nb}$	$\beta^-$ , $\gamma$ ; $\beta^-$ , $\gamma$	$^{95}\text{Zr}$ : 0.36 (55) 0.40 (43) 0.88 (2) $^{95}\text{Nb}$ : 0.16	0.73 (43) 0.76 (55) 0.77 (100)
Zirconium-97 - Niobium-97m [Note: contains $^{97}\text{Nb}$ daughter]	$^{97}\text{Zr}$ , 17 h; $^{97m}\text{Nb}$ , 1.0 m	$^{96}\text{Zr}(n,\gamma)^{97}\text{Zr} \xrightarrow{(17\text{ h})} ^{97m}\text{Nb}$ Fission product	$\beta^-$ ; $\gamma$	$^{97}\text{Zr}$ : 1.90 (~90) Others	$^{97m}\text{Nb}$ : 0.75 (92) Others

<sup>a</sup>Abundances are given in parentheses.

## STABLE ISOTOPE ENRICHMENT

Since the only difference between isotopes of an element is the number of neutrons in their nuclei, any method of separation must relate either directly or indirectly to this. Thus, techniques that take direct advantage of the mass differences come to mind first, for example, electromagnetic separation, thermal diffusion, gaseous diffusion, distillation, and ion migration. However, indirect methods that depend on slight differences in such properties as the internal vibrational and rotational frequencies of the isotopes or their excitation energies should also be useful under the proper conditions, for example, chemical exchange, photochemical enrichment, biological enrichment, electrolysis, and solvent extraction.

Electromagnetic separation, in a device known as a calutron,\* provides what is perhaps the best known "universal" technique available for isotope enrichment. The principle is illustrated in Fig. 20. Typical enrichments and available forms of the enriched materials are shown in Tables 14 and 15. Figures 21, 22, and 23 illustrate, respectively, the separation principles of gaseous diffusion, chemical exchange, and thermal diffusion.

\*The term "calutron" designates the production-type mass spectrometer, the term having been coined from the words "California University cyclotron" at the time of its development by Professor E. O. Lawrence at the University of California.

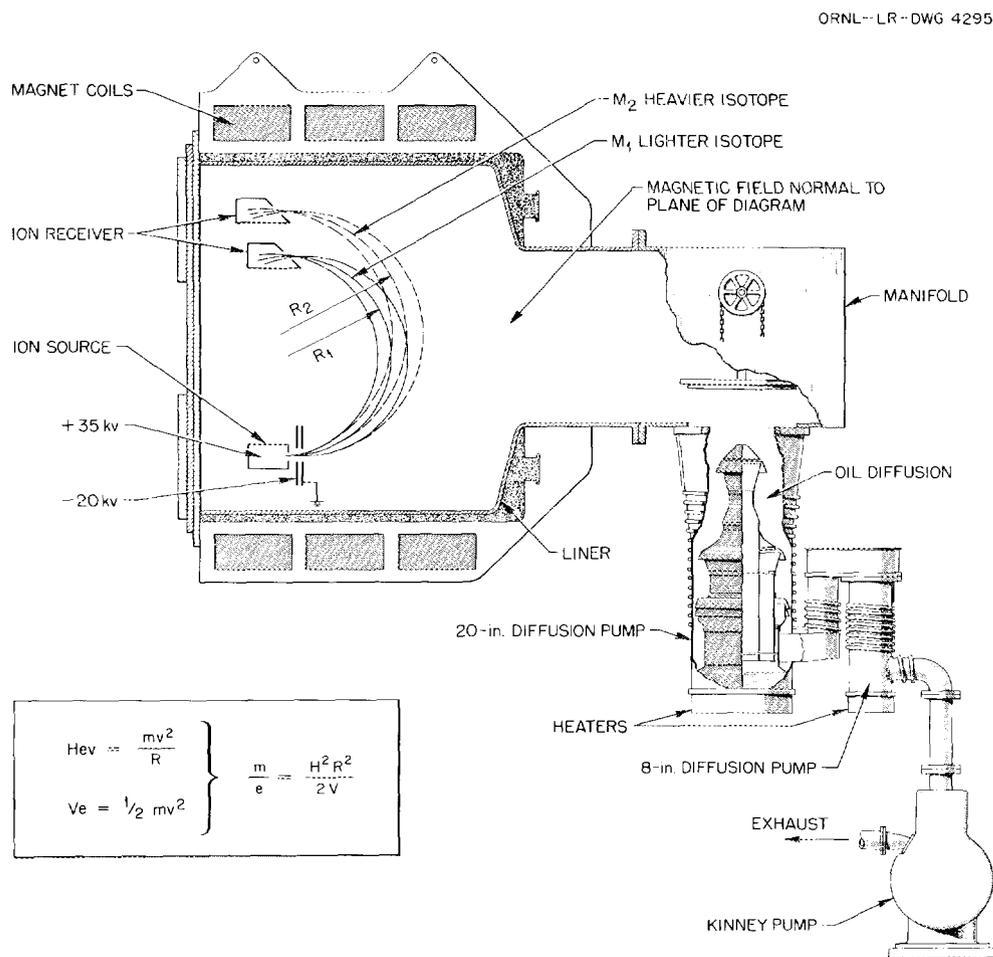


Fig. 20. Schematic Illustration of Calutron Process.

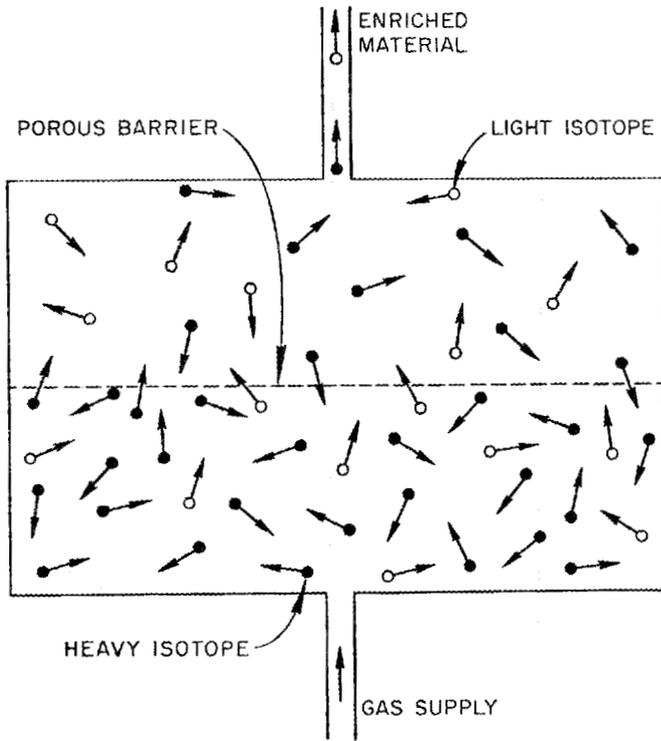
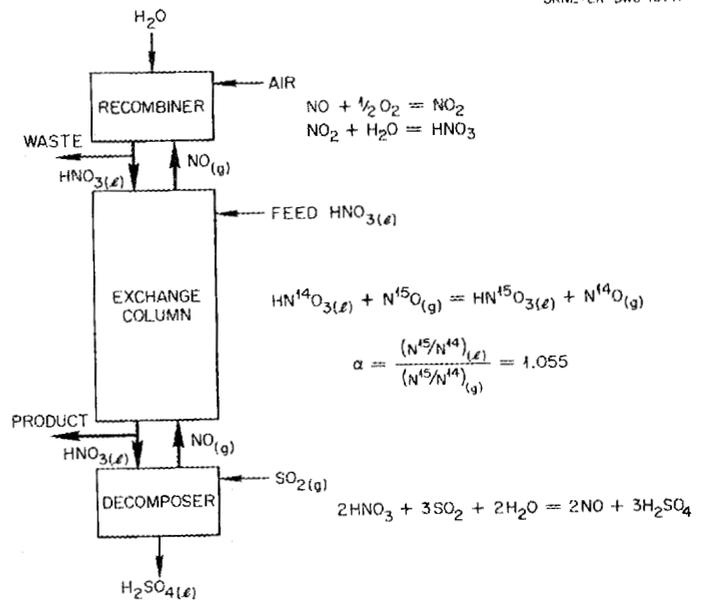


Fig. 21. Gaseous Diffusion Principle.

Fig. 22. Separation of Nitrogen Isotopes by Chemical Exchange.



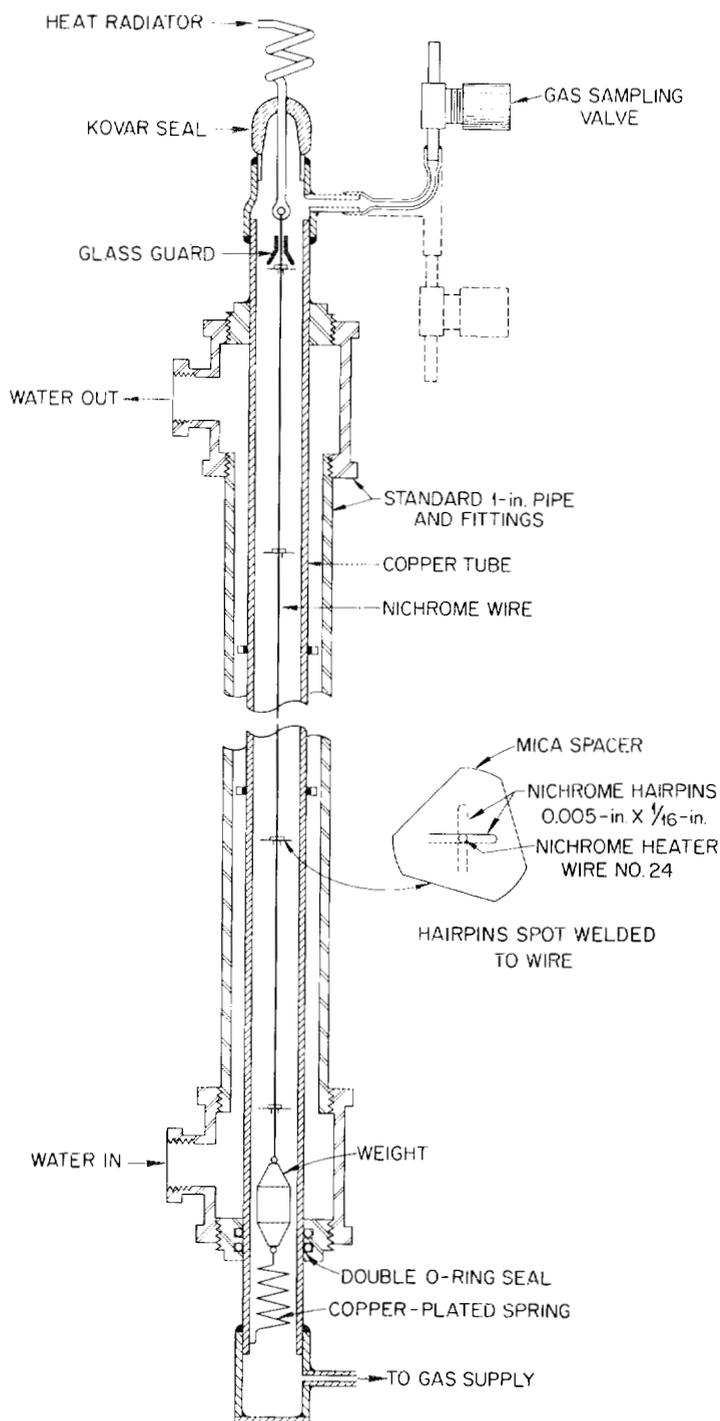


Fig. 23. Details of Hot-Wire Thermal Diffusion Column.

Table 14. Typical Calutron Enrichments of Low Natural Abundance Isotopes

Isotope	Abundance (%)	
	Normal	Enriched
Barium-132	0.101	~40
Calcium-44	2.06	>98
Calcium-46	0.0033	~40
Chromium-50	4.31	>95
Selenium-74	0.87	>50
Strontium-84	0.56	~80
Tin-112	0.95	>70
Tin-124	5.98	>90

Table 15. Typical Available Forms

Element	Form	Element	Form
Antimony	Sb	Nickel	NiO; Ni
Barium	Ba(NO <sub>3</sub> ) <sub>2</sub> ; BaCO <sub>3</sub>	Platinum	Pt
Bromine	NaBr	Potassium	KCl
Cadmium	CdO; Cd	Ruthenium	Ru
Calcium	CaCO <sub>3</sub>	Silicon	SiO <sub>2</sub>
Cerium	CeO <sub>2</sub>	Silver	Ag; AgCl
Chromium	Cr <sub>2</sub> O <sub>3</sub>	Strontium	Sr(NO <sub>3</sub> ) <sub>2</sub> ; SrCO <sub>3</sub>
Copper	CuO; Cu	Tellurium	Te
Europium	Eu <sub>2</sub> O <sub>3</sub>	Tin	SnO <sub>2</sub> ; Sn
Iron	Fe <sub>2</sub> O <sub>3</sub> ; Fe	Titanium	TiO <sub>2</sub>
Lead	Pb(NO <sub>3</sub> ) <sub>2</sub> ; PbCO <sub>3</sub>	Tungsten	WO <sub>3</sub>
Magnesium	MgO	Zinc	ZnO
Mercury	HgO; Hg(NO <sub>3</sub> ) <sub>2</sub>	Zirconium	ZrO <sub>2</sub>

Table 16. Typical Charge Materials

Element	Charge Material <sup>a</sup>	Element	Charge Material <sup>a</sup>
Antimony	<u>Sb</u> ; Sb <sub>2</sub> O <sub>3</sub> ; Sb <sub>2</sub> S <sub>3</sub> ; SbI <sub>3</sub>	Nickel	<u>NiCl<sub>2</sub></u> ; Ni(CO) <sub>4</sub>
Barium	<u>Ba</u> ; BaCl <sub>2</sub> ; BaBr <sub>2</sub>	Platinum	<u>Pt</u> <sup>c</sup>
Bromine	<u>NiBr<sub>2</sub></u> ; SrBr <sub>2</sub> <sup>b</sup>	Potassium	<u>K<sub>2</sub>CO<sub>3</sub></u> ; KI; K; KBr; KCl
Cadmium	<u>CdO + CCl<sub>4</sub></u> ; CdCl <sub>2</sub> ; CdI <sub>2</sub> ; Cd	Ruthenium	<u>RuF<sub>5</sub></u> ; Ru <sup>c</sup>
Calcium	<u>Ca</u> ; CaCl <sub>2</sub> ; CaI <sub>2</sub> ; CaO + Al	Silicon	<u>SiS<sub>2</sub></u> ; SiCl <sub>4</sub>
Cerium	<u>CeO<sub>2</sub> + CCl<sub>4</sub></u> ; CeCl <sub>3</sub>	Silver	<u>AgCl</u> ; Ag; AgBr; AgI
Chromium	<u>Cr<sub>2</sub>O<sub>3</sub> + CCl<sub>4</sub></u> ; CrCl <sub>3</sub>	Strontium	<u>Sr</u> ; SrBr <sub>2</sub>
Copper	<u>Cu<sub>2</sub>Cl<sub>2</sub></u> ; CuCl <sub>2</sub>	Tellurium	<u>Te</u> ; TeO <sub>2</sub> ; TeBr <sub>4</sub>
Europium	<u>Eu<sub>2</sub>O<sub>3</sub> + CCl<sub>4</sub></u> ; EuCl <sub>3</sub>	Tin	<u>SnS</u> ; SnCl <sub>2</sub> ; SnCl <sub>4</sub>
Iron	<u>FeCl<sub>2</sub> (fused)</u> ; FeCl <sub>3</sub>	Titanium	<u>TiCl<sub>4</sub></u>
Lead	<u>PbCl<sub>2</sub></u> ; PbI <sub>2</sub> ; (C <sub>2</sub> H <sub>5</sub> ) <sub>4</sub> Pb	Tungsten	<u>WO<sub>3</sub> + CCl<sub>4</sub></u> ; WCl <sub>6</sub> ; WBr <sub>6</sub> ; WF <sub>6</sub>
Magnesium	<u>Mg</u> ; MgCl <sub>2</sub> ; MgBr <sub>2</sub> ; MgI <sub>2</sub>	Zinc	<u>Zn</u>
Mercury	<u>HgS</u> ; HgCl <sub>2</sub> ; HgO	Zirconium	<u>ZrO<sub>2</sub> + CCl<sub>4</sub></u> ; ZrCl <sub>4</sub>

<sup>a</sup>Currently preferred forms are underlined.

<sup>b</sup>Strontium is also collected.

<sup>c</sup>Electron bombardment ion source.

The mathematical theory of electromagnetic separation involves the interrelationships among magnetic force ( $Hev$ ), centrifugal force ( $mv^2/R$ ), accelerating potential ( $V$ ), and kinetic energy,  $\frac{1}{2}mv^2$ , to give

$$\frac{m}{e} = \frac{H^2 R^2}{2V} \quad (1)$$

where

$m$  = mass of ion, grams,

$e$  = charge on ion, emu,

$H$  = magnetic field, gauss,

$R$  = radius of curvature, cm.

The velocity of the ion,  $v$  (cm/sec) is eliminated in the calculations.

If the values of  $V$ ,  $e$ , and  $H$  are fixed, it can be seen that  $m$  and  $R$  are directly related and that ions of smaller masses will have smaller radiuses of curvature; that is, the light nuclides are "bent" more than the heavy ones by the magnetic field. In practice, two sizes of calutrons are used, one with a 48-in. and the other with a 24-in. radius. The larger device has a greater separation efficiency than the smaller, but recovery from the latter is more efficient.

The basic principle behind the electromagnetic separation of isotopes is identical with that of an analytical mass spectrometer. Both depend upon high potentials for acceleration, magnetic fields for separation of isotopic ion species, ion sources for ionization of the charge materials, and receivers for retaining the separated ions — all operating in a vacuum. The notable difference is that the calutron is designed to collect usable quantities of separated isotopes, whereas the laboratory spectrometer excels as an instrument for measurement. This does not rule out the use of the latter for collecting very small amounts of virtually any isotope, although the collection rate would be very low.

Charged ions are accelerated by voltages of up to 40 kV. Typical charge materials are listed in Table 16. As these rapidly moving, singly charged positive ions move into the magnetic field surrounding the source and receiver, they are deflected or bent; the amount of deflection for a particular field strength and potential depends only upon the masses of the ions. Thus, different isotopes of a particular element traverse slightly different paths and can be intercepted in such a way as to accomplish a separation.

Table 17 lists the isotopes of several elements with typical data to show operating parameters and results of the separations. Table 14 shows enrichments of isotopes that occur in low abundance in nature.

It is, of course, possible to make "second pass" separations to obtain extremely pure samples of isotopes. For example,  ${}^6\text{Li}$ , with a natural abundance of 7.5%, has been enriched to 99.999% by virtue of a second pass. Other second pass separations have included  ${}^{40}\text{Ca}$ ,  ${}^{160}\text{Gd}$ ,  ${}^{166}\text{Er}$ ,  ${}^{168}\text{Er}$ , and  ${}^{204}\text{Pb}$ . However, these separations become quite expensive.

The procedures for chemical recovery involve, for the most part, rather straightforward inorganic techniques. Lead, for example, is recovered by leaching copper receiver pockets with  $\text{HNO}_3$ , electrodepositing the lead at the anode as  $\text{PbO}_2$ , dissolving the  $\text{PbO}_2$  in hot  $\text{HNO}_3$  and  $\text{H}_2\text{O}_2$ , and finally crystallizing high-purity  $\text{Pb}(\text{NO}_3)_2$  from 85%  $\text{HNO}_3$ . Copper is recovered by igniting graphite receiver pockets in oxygen, dissolving the ash in  $\text{HNO}_3$ , and electrolyzing the copper. This copper is then redissolved in  $\text{HNO}_3$  and ignited to  $\text{CuO}$ . Silicon is collected in graphite. The resulting silicon carbide, along with the pocket, is burned in oxygen, and the  $\text{SiO}_2$  residue is fused with  $\text{Na}_2\text{CO}_3$ . The melt is then dissolved in water, and  $\text{SiO}_2$  is precipitated by acidification and digestion with  $\text{HClO}_4$ . The chemical recovery of rare earths often involves ion exchange purifications to remove adjacent rare-earth impurities. Even then, high-purity products are difficult to obtain.

Table 17. Typical Operating Parameters and Results of Isotope Separations

Isotope	Average Beam Current (mA)	Receiver Pocket Material	Natural Abundance (%)	Enriched Abundance (%)	Product Recovered (mg/h)
Copper	50	Graphite			100
<sup>63</sup> Cu			69.1	99.90	
<sup>65</sup> Cu			30.9	99.70	
Iron	60	Graphite			115
<sup>54</sup> Fe			5.84	98.19	
<sup>56</sup> Fe			91.68	99.93	
<sup>57</sup> Fe			2.17	93.63	
<sup>58</sup> Fe			0.31	82.12	
Tellurium	20	Aluminum			70
<sup>120</sup> Te			0.089	53.39	
<sup>122</sup> Te			2.46	95.44	
<sup>123</sup> Te			0.87	83.8	
<sup>124</sup> Te			4.61	95.10	
<sup>125</sup> Te			6.99	95.56	
<sup>126</sup> Te			18.71	98.69	
<sup>128</sup> Te			31.79	99.46	
<sup>130</sup> Te			34.49	99.49	
Ruthenium	7	Graphite			27
<sup>96</sup> Ru			5.47	98.07	
<sup>98</sup> Ru			1.84	89.00	
<sup>99</sup> Ru			12.77	98.8	
<sup>100</sup> Ru			12.56	97.24	
<sup>101</sup> Ru			17.10	97.73	
<sup>102</sup> Ru			31.70	99.53	
<sup>104</sup> Ru	18.56	99.7			
Magnesium	100	Copper + oxygen gas			80
<sup>24</sup> Mg			78.60	99.92	
<sup>25</sup> Mg			10.11	97.87	
<sup>26</sup> Mg			11.29	99.77	

### Stable Isotope Utilization

Why separate stable isotopes? Isotopes are enriched in order to take advantage of the fact that the magnitude of any effect which can be associated with a particular isotope depends directly upon the amount of that isotope present. Hence enriched isotopes are particularly valuable in cases where the natural abundance is low.

A very important use is in the preparation of radioisotopes. In neutron or charged-particle activations, for example, the yield resulting from a given irradiation is directly related to the concentration of target isotope. Frequently, it is economically advantageous to substitute calutron time for reactor or accelerator time — that is, to reduce activation time by increasing target-isotope concentration. On the other hand, for a given activation time, a product with better specific activity is obtained when enriched targets are used (enriched <sup>108</sup>Cd, <sup>84</sup>Sr, <sup>54</sup>Fe, <sup>58</sup>Fe, <sup>74</sup>Se, <sup>44</sup>Ca, <sup>46</sup>Ca, and <sup>50</sup>Cr are routinely irradiated by neutrons for the production of high-specific-activity radioisotopes).

Table 18. Enrichment of Calcium and Iron

	Isotope	Natural Abundance (%)	Enriched Abundance (%)
Desired product	$^{46}\text{Ca}$	0.0033	45.0
Contaminant	$^{44}\text{Ca}$	2.06	3.3
Desired product	$^{58}\text{Fe}$	0.31	78.4
Contaminant	$^{54}\text{Fe}$	5.84	0.9

A further advantage associated with any enrichment procedure may be the simultaneous depletion of other isotopes. Often this latter effect is more important than the actual enrichment itself. For example, the preparation of 4.5-day  $^{47}\text{Ca}$  involves an  $(n,\gamma)$  reaction on  $^{46}\text{Ca}$ . However, the low abundance (0.0033%) of  $^{46}\text{Ca}$  in natural calcium is so overshadowed by the relatively high abundance (2.06%) of  $^{44}\text{Ca}$  that any irradiation of natural calcium gives primarily the radioisotope  $^{45}\text{Ca}$  instead of  $^{47}\text{Ca}$ . Electromagnetic enrichment of  $^{46}\text{Ca}$  gives a product with  $\sim 15:1$   $^{46}\text{Ca}:$  $^{44}\text{Ca}$  ratio instead of the  $\sim 1:600$  ratio in normal calcium.

A similar situation exists with respect to  $^{55}\text{Fe}$  in  $^{59}\text{Fe}$ . The use of enriched  $^{58}\text{Fe}$  as the reactor target results in a reduction in the ratio of  $^{55}\text{Fe}:$  $^{59}\text{Fe}$  by a factor of  $>1500$ . Table 18 shows the effects of separation on the two isotopes involved for calcium and for iron.

The use of separated isotopes in making measurements of fundamental physical properties is very common. The determination of cross sections or decay schemes, for instance, would be essentially impossible without enriched species. (Tin has ten isotopes,  $^{115}\text{Sn}$  having an abundance of 0.35%. To assign values specifically to this isotope in the presence of 99.65% of the other nine nuclides could not be done with any confidence. But when enriched to 40%  $^{115}\text{Sn}$ , a measurement becomes readily interpretable.)

Table 19 categorizes and lists the most common uses of enriched stable isotopes.

Table 19. Uses of Enriched Stable Isotopes

**Ground-state studies**

Moments and Spins

Decay

Half-lives

Disintegrations or radiations

Decay schemes

Angular correlation (e.g., of  $\gamma$ 's from disintegrations)

Isomeric levels

Isomerism

Isomeric transitions

Radioactivity

**Reaction studies**

Production and Genetics

Mass assignments

New isotopes (production and measurement)

Identification of particles in reaction (includes  $\gamma$ 's)

Spectral studies of outgoing radiations

Energy Levels

Excited states

Coulomb excitation

Cross Sections and Yields (e.g.,  $n$ 's from  $d$ 's on  ${}^6\text{Li}$ )

Neutrons

Fission

Elastic scattering

Inelastic scattering

Angular distribution

Charged particles

Fission

Elastic scattering

Inelastic scattering

Angular distribution

Photons

**Nonnuclear applications**

Biology, Medicine, Agriculture, Geology

Chemistry Applications (includes isotope dilution)

Analytical Methods

General Physics

Hyperfine structure

Isotope shift

Natural abundance

**Miscellaneous**

Isotope Effects

Isotopic Composition

Nuclear Alignments

Optical Studies

Radioisotope Production

Spectral Studies

Stable Isotope Separation

Stable Isotope Uses

Target Fabrication

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#### AVAILABILITY OF ENRICHED STABLE ISOTOPES

The stable isotopes listed below are typical of those for sale from Oak Ridge National Laboratory and from commercial suppliers.\* Although stable isotopes can be procured without AEC license, an *export* license from the U.S. Department of Commerce, Bureau of International Commerce, Office of Export Control, Washington, D.C. 20230, is required for certain quantities and values of lithium, boron, heavy water, and deuterium products. Other isotopes need no export license except to non-free-world destinations.

Unless otherwise indicated, natural abundances of the stable isotopes in the tabulation are taken from *Isotopic Mass Spectrometry of the Elements*, USAEC Report ORNL-3528, compiled by E. J. Spitzer and J. R. Sites (December 1963).

Prices are, of course, available from suppliers and, for any particular isotope, increase almost exponentially with enrichment. Although never cheap in terms of pound quantities (e.g.,  $^{46}\text{Ca}$  enriched to >40% would cost approximately \$320 million per pound, if such a quantity were available), milligram amounts are usually sufficient for most uses, and the cost becomes quite reasonable — particularly since the enriched form permits experiments or other uses that would otherwise be impossible.

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\*For listing, see *The Isotope Index* (James L. Sommerville, Ed.), published by Scientific Equipment Co., P.O. Box 19086, Indianapolis, Ind. 46219.

Element	Usual Inventory Form	Nuclide	Natural Abundance <sup>a</sup> (%)	Enriched Abundance (%)
Antimony (Sb)	Sb	121	57.25	95 to 99.5
		123	42.75	95 to 99
Argon (Ar)	Ar	36	0.337	Up to >55
		38	0.063	2 to >50
Barium (Ba)	Ba(NO <sub>3</sub> ) <sub>2</sub>	130	0.101	10 to >50
		132	0.097	5 to 45
		134	2.42	40 to 85
		135	6.59	50 to >90
		136	7.81	30 to >90
		137	11.32	40 to 90
		138	71.66	>95
Boron (B)	B	10	19.61	92
		11	80.39	98
	BF <sub>3</sub> · CaF <sub>2</sub>	11	80.39	89
Bromine (Br)	NaBr	79	50.537	90 to >98
		81	49.463	90 to >97
Cadmium (Cd)	CdO	106	1.215	70 to 90
		108	0.875	60 to 85
		110	12.39	50 to 98
		111	12.75	80 to 98
		112	24.07	80 to 98
		113	12.26	80 to >95
		114	28.86	90 to >98
		116	7.58	60 to >99
Calcium (Ca)	CaCO <sub>3</sub>	40	96.97	99 to >99.9
		42	0.64	25 to >90
		43	0.145	20 to >80
		44	2.06	75 to >98
		46	0.0033	20 to 47
		48	0.185	5 to >95
		Carbon (C)	C	12
13	1.108			>90
Cerium (Ce)	CeO <sub>2</sub>	136	0.193	10 to 40
		138	0.25	3 to 18
		140	88.48	>98
		142	11.07	>80
Chlorine (Cl)	NaCl	35	75.529	85 to >98
		37	24.471	60 to >95
Chromium (Cr)	Cr <sub>2</sub> O <sub>3</sub>	50	4.31	70 to 95
		52	83.76	Up to >99.9
		53	9.55	80 to >95
		54	2.38	70 to >95
Copper (Cu)	CuO	63	69.09	>98
		65	30.91	>90
Dysprosium (Dy)	Dy <sub>2</sub> O <sub>3</sub>	156	0.0524	9 to 25
		158	0.0902	5 to 25
		160	2.294	50 to 70
		161	18.88	70 to 90
		162	25.53	70 to 90
		163	24.97	70 to 90
		164	28.18	65 to 95

Element	Usual Inventory Form	Nuclide	Natural Abundance <sup>d</sup> (%)	Enriched Abundance (%)
Erbium (Er)	Er <sub>2</sub> O <sub>3</sub>	162	0.136	5 to 25
		164	1.56	10 to 65
		166	33.41	70 to >99
		167	22.94	50 to 95
		168	27.07	70 to 99.9
		170	14.88	80 to 97
Europium (Eu)	Eu <sub>2</sub> O <sub>3</sub>	151	47.82	90 to 99
		153	52.18	90 to 99
Gadolinium (Gd)	Gd <sub>2</sub> O <sub>3</sub>	152	0.20	13 to 40
		154	2.15	25 to 75
		155	14.73	65 to 95
		156	20.47	80 to 97
		157	15.68	60 to 95
		158	24.87	80 to 99
Gallium (Ga)	Ga <sub>2</sub> O <sub>3</sub>	69	60.4	90 to >99
		71	39.6	>90
Germanium (Ge)	GeO <sub>2</sub>	70	20.52	80 to 95
		72	27.43	80 to 98
		73	7.76	70 to 95
		74	36.54	90 to 99
		76	7.76	70 to 99
Hafnium (Hf)	HfO <sub>2</sub>	174	0.18	3 to 20
		176	5.20	40 to 85
		177	18.50	55 to 95
		178	27.14	80 to 96
		179	13.75	40 to 85
		180	35.24	90 to 99
Hydrogen (H) [Hydrogen-2 is commonly referred to as deuterium (symbol D)]	HD, D <sub>2</sub> , HDO, D <sub>2</sub> O, and (CD <sub>2</sub> ) <sub>x</sub> (polyethylene)	2	0.015	>98
Indium (In)	In <sub>2</sub> O <sub>3</sub>	113	4.28	30 to 88
		115	95.72	>99.5
Iridium (Ir)	Ir	191	37.3	85 to 96
		193	62.7	85 to >95
Iron (Fe)	Fe <sub>2</sub> O <sub>3</sub>	54	5.82	75 to >90
		56	91.66	98 to >99.8
		57	2.19	40 to >90
		58	0.33	25 to 90
Krypton (Kr)	Kr	78	0.354	~8
		86	17.37	>90
Lanthanum (La)	La <sub>2</sub> O <sub>3</sub>	138	0.089	0.3 to 8.0
		139	99.911	>99.95
Lead (Pb)	Pb(NO <sub>3</sub> ) <sub>2</sub>	204	1.48	20 to >99
		206	23.6	88 to >99.95
		207	22.6	25 to >99.9
		208	52.3	80 to >99
Lithium (Li)	Li	6	7.42	95.4 to 99.3
		7	92.58	99.99
	LiOH·H <sub>2</sub> O	7	92.58	99.99
	Li <sub>2</sub> CO <sub>3</sub>	6	7.42	95.4 to >99.3
		7	92.58	99.99

(Lithium metal, LiH, LiD, LiF also available)

Element	Usual Inventory Form	Nuclide	Natural Abundance <sup>a</sup> (%)	Enriched Abundance (%)	
Lutetium (Lu)	Lu <sub>2</sub> O <sub>3</sub>	175	97.41	>99.8	
		176	2.59	70 to 80	
Magnesium (Mg)	MgO	24	78.70	>99	
		25	10.13	>90	
		26	11.17	>95	
Mercury (Hg)	HgO	196	0.146	5 to 49	
		198	10.02	50 to >99	
		199	16.84	50 to 90	
		200	23.13	50 to 90	
		201	13.22	80 to 90	
		202	29.80	70 to 99	
		204	6.85	35 to >80	
Molybdenum (Mo)	Mo	92	15.84	90 to 98	
		94	9.04	70 to 95	
		95	15.72	70 to 99	
		96	16.53	85 to 97	
		97	9.46	85 to 95	
		98	23.78	90 to 99	
Neodymium (Nd)	Nd <sub>2</sub> O <sub>3</sub>	100	9.63	80 to 99	
		142	27.11	80 to 99	
		143	12.17	65 to 95	
		144	23.85	85 to 99	
		145	8.30	55 to 95	
		146	17.22	85 to 99	
Neon (Ne)	Ne	148	5.73	80 to 95	
		150	5.62	55 to 97	
		20	90.92	>99.9	
		21	0.26	~6	
Nickel (Ni)	Ni	22	8.82	>96	
		58	67.88	98 to >99	
		60	26.23	86 to 99.8	
		61	1.19	70 to >95	
Nitrogen (N)	HNO <sub>3</sub>	62	3.66	95 to 99	
		64	1.08	95 to >99	
		15	0.365	Up to >99	
		Osmium (Os)	Os	184	0.018
186	1.59			60 to 65	
187	1.64			45 to 50	
188	13.3			>85	
189	16.1			>85	
190	26.4			>95	
192	41.0			>95	
Oxygen <sup>b</sup> (O)	H <sub>2</sub> O	17	0.037	10	
		18	0.204	7 to 98	
Palladium (Pd)	D <sub>2</sub> O	18	0.204	2 to 89	
		Pd	102	0.96	50 to 65
			104	10.97	55 to 85
			105	22.23	70 to 80
			106	27.33	70 to 85
			108	26.71	85 to 95
110	11.81		75 to 95		

Element	Usual Inventory Form	Nuclide	Natural Abundance <sup>a</sup> (%)	Enriched Abundance (%)
Platinum (Pt)	Pt	190	0.0127	0.1 to 0.9
		192	0.78	4 to 15
		194	32.9	40 to 70
		195	33.8	45 to 65
		196	25.3	40 to 70
		198	7.21	30 to 65
Potassium (K)	KCl	39	93.10	>99
		40	0.01181	3 to >80
		41	6.88	85 to 99.5
Rhenium (Re)	Re	185	37.07	80 to 99
		187	62.93	95 to >99
Rubidium (Rb)	RbCl	85	72.15	95 to >98
		87	27.85	65 to >99
Ruthenium (Ru)	Ru	96	5.51	60 to >90
		98	1.87	40 to >85
		99	12.72	75 to >90
		100	12.62	71 to >90
		101	17.07	65 to >95
		102	31.61	>90
Samarium (Sm)	Sm <sub>2</sub> O <sub>3</sub>	104	18.58	90 to 99
		144	3.09	70 to >90
		147	14.97	80 to 99
		148	11.24	70 to >99
		149	13.83	80 to 99
		150	7.44	60 to >99.7
		152	26.72	85 to 99
Selenium (Se)	Se	154	22.71	>96
		74	0.87	12 to >40
		76	9.02	35 to 90
		77	7.58	50 to 90
		78	23.52	70 to 98
		80	49.82	90 to 99
Silicon (Si)	SiO <sub>2</sub>	82	9.19	40 to 90
		28	92.21	>98
		29	4.70	60 to >85
		30	3.09	40 to >90
Silver (Ag)	Ag	107	51.35	90 to >99
		109	48.65	>99
Strontium <sup>c</sup> (Sr)	Sr(NO <sub>3</sub> ) <sub>2</sub>	84	0.56	60 to >80
		86	9.86	65 to 98
		87	7.02	55 to 98
		88	82.56	>98
Sulfur (S)	S	32	95.0	>98
		33	0.760	4 to 26
		34	4.22	10 to 50
		36	0.0136	2.0 to 2.4
Tantalum (Ta)	Ta <sub>2</sub> O <sub>5</sub>	180	0.0123	0.10 to 5.1
Tellurium (Te)	Te	120	0.089	11 to 50
		122	2.46	71 to 95
		123	0.87	25 to 80
		124	4.61	49 to 95
		125	6.99	40 to 97
		126	18.71	85 to 97
		128	31.79	80 to >99
		130	34.48	75 to 99

Element	Usual Inventory Form	Nuclide	Natural Abundance <sup>a</sup> (%)	Enriched Abundance (%)
Thallium (Tl)	Tl <sub>2</sub> O <sub>3</sub>	203	29.50	45 to 95
		205	70.50	80 to 99
Tin (Sn)	SnO <sub>2</sub>	112	0.96	>65
		114	0.66	45 to >55
		115	0.35	11 to 41
		116	14.30	75 to >95
		117	7.61	45 to 90
		118	24.03	90 to 99
		119	8.58	>75
		120	32.85	90 to 99
		122	4.72	75 to 95
		124	5.94	80 to 96
Titanium (Ti)	TiO <sub>2</sub>	46	7.93	70 to 90
		47	7.28	60 to 90
		48	73.94	>96.5
		49	5.51	25 to 90
		50	5.34	65 to 85
Tungsten (W)	WO <sub>3</sub>	180	0.135	4 to 14
		182	26.41	90 to 95
		183	14.4	>70
		184	30.64	80 to 96
		186	28.41	>96
Vanadium (V)	V <sub>2</sub> O <sub>5</sub>	50	0.24	15 to 45
		51	99.76	>99.95
Xenon (Xe)	Xe	124	0.096	~1
		131	21.2	25
		136	8.87	80
Ytterbium (Yb)	Yb <sub>2</sub> O <sub>3</sub>	168	0.135	10 to 35
		170	3.03	60 to 80
		171	14.31	85 to >95
		172	21.82	85 to 98
		173	16.13	75 to 95
		174	31.84	85 to 99
		176	12.73	75 to 99
Zinc (Zn)	ZnO	64	48.89	85 to 99
		66	27.81	90 to 99
		67	4.11	50 to 95
		68	18.57	95 to 99
		70	0.62	55 to >75
Zirconium (Zr)	ZrO <sub>2</sub>	90	51.46	90 to 99
		91	11.23	45 to 90
		92	17.11	80 to 96
		94	17.40	80 to 99
		96	2.80	45 to 90

<sup>a</sup>In several cases, not all isotopes of an element are provided as enriched products (e.g., Ar, H, Kr, N). In these cases, only the enriched nuclides are listed; hence, the natural abundances do not total 100%.

<sup>b</sup>A. O. Nier, A Redetermination of the Relative Abundances of the Isotopes of Carbon, Nitrogen, Oxygen, Argon, and Potassium, *Phys. Rev.* 77: 789–93 (1950).

<sup>c</sup>A. O. Nier, The Isotopic Constitution of Strontium, Barium, Bismuth, Thallium, and Mercury, *Phys. Rev.* 54: 275–78 (1938).

## SPECIAL MATERIALS AND SERVICES

Occasionally there are requirements for special reactor or cyclotron irradiations or other services such as target fabrication, conversion of one product form to another, or purification of research materials. These services are available from various organizations on a custom-service basis.

**Reactor Irradiations.** -- Special service irradiations -- for example, in connection with neutron activation analysis -- are quite common and are available from most organizations that have reactors. Several organizations provide the complete service, that is, irradiation and analysis.

**Cyclotron Irradiations.** -- There are several production cyclotrons in operation, among which the Oak Ridge National Laboratory 86-in. is one of the largest.\* It develops internal proton-beam currents up to 3 mA at 17.5 MeV and up to 1.5 mA at 21 MeV. Flat-plate and capsule targets are both used; typical production information is shown in Table 20. Table 21 lists additional isotopes that have been produced in cyclotrons.

Although no AEC license is required for cyclotron-produced activities, most license-agreement states do require a license for these materials.

**Special Research Materials.** -- The heavy elements  $^{241}\text{Am}$  and  $^{237}\text{Np}$  are available from Oak Ridge National Laboratory. The ordering procedure is the same as for other radioisotopes.

**Sources.** -- A wide variety of source forms and source designs is available from commercial organizations and national laboratories. Cobalt-60,  $^{192}\text{Ir}$ , Sb-Be neutron sources, and fission product

Table 20. Production Information for Cyclotron Isotopes

Radioisotope	Flat-Plate Target		Capsule Target	
	Material	Estimated yield/h $\pm 25\%$	Material	Estimated yield/h $\pm 25\%$
$^7\text{Be}$	Li on Cu	30 mCi		
$^{22}\text{Na}$	Mg solid	300 $\mu\text{Ci}$		
$^{48}\text{V}$			$\text{TiO}_2$	23 mCi
$^{51}\text{Cr}$	V solid	120 mCi		
$^{52}\text{Mn}$			Cr powder	52 mCi
$^{55}\text{Fe}$	Mn on Al	8 mCi		
$^{57}\text{Co}$	Ni on Cu	17 mCi		
$^{68}\text{Ge}$	Ga on Cu	3 mCi		
$^{74}\text{As}$			Ge powder	19 mCi
$^{84}\text{Rb}$			Kr gas	700 $\mu\text{Ci}$
$^{85}\text{Sr}$			RbCl	3 mCi
$^{88}\text{Y}$			$\text{SrCO}_3$	3 mCi
$^{109}\text{Cd}$	Ag solid	9 mCi		
$^{123}\text{I}$			$^{123}\text{Te}$ enriched	100 mCi
$^{139}\text{Ce}$			$\text{La}_2\text{O}_3$	1 mCi
$^{181}\text{W}$	Ta on Cu	15 mCi		
$^{195}\text{Au}$	Pt on Cu	9 mCi		
$^{207}\text{Bi}$	Pb on Cu	300 $\mu\text{Ci}$		

\*J. J. Pinajian and T. A. Butler, ORNL 86-in. Cyclotron for Isotope Production, *Isotopes Radiation Technol.* 1(2): 137-43 (1963).

Table 21. Additional Cyclotron-Produced Isotopes

The following radioisotopes have not been produced in sufficient amounts to give reliable estimates of yield. Contact the supplier concerning these or any other radioisotope of interest.

$^{105}\text{Ag}$	$^{153}\text{Gd}$	$^{57}\text{Ni}$	$^{193}\text{Pt}$	$^{123m}\text{Te}$
$^{26}\text{Al}$	$^{197}\text{Hg}$	$^{91}\text{Nb}$	$^{183}\text{Re}$	$^{44}\text{Ti}$
$^{73}\text{As}$	$^{124}\text{I}$	$^{103}\text{Pd}$	$^{99}\text{Rh}$	$^{201}\text{Tl}$
$^{203}\text{Bi}$	$^{125}\text{I}$	$^{203}\text{Pb}$	$^{102}\text{Rh}$	$^{202}\text{Tl}$
$^{77}\text{Br}$	$^{126}\text{I}$	$^{143}\text{Pm}$	$^{44m}\text{Sc}$	$^{165}\text{Tm}$
$^{56}\text{Co}$	$^{130}\text{I}$	$^{144}\text{Pm}$	$^{48}\text{Sc}$	$^{168}\text{Tm}$
$^{132}\text{Cs}$	$^{170}\text{Lu}$	$^{145}\text{Pm}$	$^{113}\text{Sn}$	$^{49}\text{V}$
$^{147}\text{Eu}$	$^{171}\text{Lu}$	$^{146}\text{Pm}$	$^{179}\text{Ta}$	$^{86}\text{Y}$
$^{148}\text{Eu}$	$^{172}\text{Lu}$	$^{148}\text{Pm}$	$^{95}\text{Tc}$	$^{87}\text{Y}$
$^{149}\text{Eu}$	$^{174}\text{Lu}$	$^{149}\text{Pm}$	$^{96}\text{Tc}$	$^{88}\text{Zr}$
$^{151}\text{Gd}$	$^{93}\text{Mo}$	$^{191}\text{Pt}$	$^{121}\text{Te}$	$^{65}\text{Zn}$

sources (e.g.,  $^{137}\text{Cs}$ ,  $^{144}\text{Ce}$ ,  $^{90}\text{Sr}$ ,  $^{147}\text{Pm}$ ) are relatively inexpensive sources that can be used in many applications, including radiography, teletherapy, heat generation, and batteries.

**Special Calutron Services: Ion Implantation.** — On request, services other than isotope separation can be scheduled in the ORNL calutrons. The use of discrete ion beams for ion implantation in the “doping” of semiconductors, the formation of accelerator targets, and the preparation of samples for diffusion studies are typical of the additional services available. Bombardment techniques provide implantation of any stable nuclide (and some radionuclides) within the energy range 10 to 40 keV, and at current densities of  $<1 \mu\text{A}/\text{cm}^2$  to  $>150 \text{mA}/\text{cm}^2$ . Through the use of doubly charged ions and specially designed receiver assemblies, the energy range can be expanded to include bombardments within the energy range  $\sim 10$  to 160 keV. Surface particle densities of  $>10^{12}$  particles/ $\text{cm}^2$  can be achieved, and gas targets can be formed to contain 5 to 20  $\mu\text{g}/\text{cm}^2$  on suitable backings.

Receiver assemblies have been designed which are capable of providing multiple-target bombardments (up to 100 targets per run for certain types), and rotating assemblies are used to ensure uniform deposition of the ionic species.

**Preparation of Special Research Forms.** — Preparation of special research forms of the various stable and radioactive isotopes and elements (including transuranium elements) is a service performed by the Oak Ridge National Laboratory Isotopes Target Center for all AEC laboratories and contractors. On a special request basis other research organizations are given consideration for this service. Research material preparations include chemical conversions of inventory forms of the isotopes to those forms desired, but do not include labeled organic compound preparations. Special physical forms that can be obtained include thin films and foils for use as accelerator targets and metal in the form of bars, wires, and sheets formed by casting, rolling, pressing, and sintering. Further purification of isotopic materials can be performed by chemical means or by techniques such as crystal-bar preparation (Van Arkel–deBoer process) and zone refining. In some cases, single-crystal preparation is possible either in thin-film form or as bulk material.

As a guide to the research scientist, the listing below (Table 22) exemplifies the capabilities of the Isotopes Target Center. Note: Many preparations are not listed, and the range of thickness can be increased or decreased, depending on sample size, shape, etc.

Table 22. Target Preparations

Code: a -- evaporation  
 b -- rolling  
 c -- electrolytic deposition  
 d -- casting or pressing  
 f -- other

1 -- self-supporting  
 2 -- metal backing  
 3 -- thin carbon

Element	Range of Thickness ( $\mu\text{g}/\text{cm}^2$ )	Method of Preparation	Backing	Form of Deposit
Aluminum	5 to 12,000	a	2	Al
	150 up	a	1	Al
		d	1	Al
Americium	Undetermined	a		Am or oxide
Antimony	500 to 3000	a	1	Sb
Arsenic	10 to 200	a	2	As
Barium	10 to 1000	a	2	Salt
		d	1	Salt
	2000 up	a, b	1, 2	Ba
Beryllium	Undetermined	a	1, 2, 3	Be
Bismuth	10 to undetermined	a	2	Bi
Boron	20 to 250	a	1	B
	10 to 1000	a	2	B
Bromine	10 to 1000	a	2	Bromide
	5000 up	d	1	Bromide
Cadmium	10 to 200	a	2	Cd
	1000 up	b	1	Cd
		d	1	Cd
Calcium	10 to 1000	a	2	Ca
	700 up	b	1	Ca
		d		
Carbon				
Normal	10 to 200	a	1	C
Isotopic	10 to 200	f	2	C
Cerium	10 to undetermined	a	2	Oxide
Cesium	10 to 1000	a	2	Salt
Chlorine	10 to 1000	a	2	Salt
	5000 up	d	1	Salt
Chromium	500 to 3000	a	1	Cr
	10 to undetermined	a	2	Cr
		d	1	Cr
Cobalt	1000 up	b	1	Co
	10 up	a	2	Co
	100-1000	a	1	Co
Copper	500 up	b	1	Cu
	10 to 1000	c	2	Cu
	200 up	a	1	Cu
		d	1	Cu
Erbium	10 to undetermined	a	2	Er
	Undetermined	a	1	Er
Europium	10 to undetermined	a	2	Eu
	1000 up	b	1	Eu
Fluorine	25 to 500	a	2	Fluoride
Gallium	10 to undetermined	a	2	Ga
	10 to 200	a	3	$\text{Ga}_2\text{O}_3$
		d	1	$\text{Ga}_2\text{O}_3$
Germanium	10 up	a	2	Ge
	300 to undetermined	a	1	Ge

Table 22 (continued)

Element	Range of Thickness ( $\mu\text{g}/\text{cm}^2$ )	Method of Preparation	Backing	Form of Deposit
Gold	10 up	a	2	Au
	Undetermined		1	Au
<sup>3</sup> H adsorbed on Zr, Y, Ti, or Er	100 to 5000	d	1	Au
		f	2	
Indium	5000 up	b	1	In
	10 up	a	2	In
		d	1	In
Iridium	10 to 100	a	2	Ir
Iron	500 up	b	1	Fe
	10 up	a	2	Fe
		d	1	Fe
Lanthanum	10 to undetermined	a	2	La
		d	1	La
Lead	8000 up	b	1	Pb
	1000 to 8000	a	1	Pb
	10 to 1000	a	2	Pb
Lithium	4000 to any cast size	d		
		b, d	1	Li
		a	3	LiH
		a	2	Li
Lutetium	10 to undetermined	a	2	Lu
Magnesium	250 to 1000	b	1	Mg
	1000 to 8000	a	1	Mg
		d	1	Mg
Manganese	300 to 1600	a	1	Mn
	10 to undetermined	a	2	Mn
Mercury	1000 to 4000	c	on Au	Hg
	Undetermined	a	2	Salt
Molybdenum	10 to 1000	a	2	Mo
	1000 up	b	1	Mo
Neodymium	10 to undetermined	a	2	Nd
Neptunium	10 up	a	2, 3	Oxide
Nickel	500 up	b	1	Ni
	10 up	a	2	Ni
		d	1	Ni
Niobium	10 up	a	2	Nb
	1000 up	b	1	Nb
Palladium	1000 up	b	1	Pd
	10 up	a	2	Pd
		d	1	Pd
Platinum	4000 up	b	1	Pt
	10 up	a	2	Pt
		d	1	Pt
Plutonium	10 up	a	2	Oxide
Polonium	10 up	a	2, 3	Po
Potassium	7500 to any cast size	b, d	1	K
Promethium	10 up	a	2	Oxide
		a	2	Pm
Radium	10 up	a	2	Bromide
Samarium	1000 to undetermined	b	1	Sm
	10 up	a	2	Sm
Scandium	10 up	a	2	Sc
	1000 up	b	1	Sc

Table 22 (continued)

Element	Range of Thickness ( $\mu\text{g}/\text{cm}^2$ )	Method of Preparation	Backing	Form of Deposit
Selenium	300 to 5000	a	1	Se
	10 to 5000	a	2	Se
		d	1	Se
Silver	1000 up	b	1	Ag
	100 to 5000	a	1	Ag
	10 to 1000	a	2	Ag
		d	1	Ag
Silicon	10 to 1000	a	2	Si
	50 to 400	a	1	Si
	10 to 150	a	2, 5	SiO <sub>2</sub>
Sodium	7500 to any cast size	b, d	1	Na
Strontium	3000 up	b	1	Sr
Sulfur	5000 up	d	1	S
	10 to 100	a	2	S
Tantalum	2000 up	b	1	Ta
	10 to 1000	a	2	Ta
Technetium	10 to 1000	a	2	Tc
Tellurium	10 to 1000	a	2, 3	Te
		d	1	Te
Thallium	8000 up	b	1	Tl
	10 up	a	2	Tl
Thorium	4000 up	b	1	Th
Tin	4000 up	b	1	Sn
	10 to 1000	a	2	Sn
	500 to 4000	a	1	Sn
Titanium	500 up	b	1	Ti
	10 up	a	2	Ti
Tungsten	In Cu matrix	b	2	W
	>2000	d	1	W
Uranium	10 up	a	2	Oxide
	0.1 mil up	b	1	U
Vanadium	1000 up	b	1	V
	10 up	a	2	V
Ytterbium	10 to undetermined	a	2	Yb
	1000 up	b	1	Yb
Yttrium	10 to undetermined	a	2	Y
	2000 up	b	1	Y
Zinc	1000 up	b	1	Zn
	10 up	a	2	Zn
Zirconium	500 up	b	1	Zr
	10 to 5000	b	2	Zr

**Selected References**

*Radioisotopes, Stable Isotopes, Research Materials*, Oak Ridge National Laboratory, Isotopes Sales Department, P.O. Box X, Oak Ridge, Tennessee 37830, 1967.

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