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A SURVEY OF NEUTRON SOURCES AND THEIR APPLICATIONS

A. Lorenz

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A Survey of Neutron Sources and Their Applications

Abstract

This survey is an introduction to the general characteristics and fundamental properties of neutron sources. The emphasis is on natural and isotopic

sources, their uses and applications. Comprehensive tabulations of isotopic source reaction data and an ample bibliography are included.

I. Introduction

Neutron sources have wide applications in scientific research as well as in industry. The varied characteristics of these sources, namely magnitude of their yield, energy distribution of the emitted neutrons and whether their emission is of a steady-state or pulsed type, makes them versatile analytical tools which have found their way into numerous fields. It is the object of this survey to describe the different types of neutron sources, man-made and natural, and to illustrate their applications.

Generally, neutron sources can be classified according to the method of neutron production:

- Nuclear reactors and nuclear explosions
- Charged particle accelerators
- Isotope sources
- Spontaneous and induced fission sources

For the purpose of this survey, the term "neutron source" will exclude those source potentials associated with power or research reactor installations, nuclear physic research laboratories, or nuclear

explosives. The neutron sources of interest here fall into two major categories: manufactured neutron-producing instruments and naturally occurring neutron-producing reactions which may or may not be engineered for specific applications. Because of their wide use, considerable emphasis has been put on isotopic neutron sources, and a comprehensive tabulation of most potential (α, n), photoneutron, and spontaneous fission sources are given in the text. A number of representative examples to illustrate the uses and applications of neutron sources are given in Chapter V of this survey, and an ample bibliography is provided for further reference. Chapter VI gives a brief outline of natural background neutron levels. With regard to specific and more detailed descriptions of neutron source applications, the reader is referred to the proceedings of the recently held "Neutron Sources and Applications" conference (Augusta, Georgia, April 1971) sponsored by the American Nuclear Society (AU71).

II. General Characteristics of Neutron Sources

Great numbers of various neutron sources, differing one from another in their properties and basic parameters, are presently in use. The most general classifying characteristic of neutron sources is the method of neutron production, determined by the nuclear physics process which forms the basis of a given source. Accordingly, neutron sources can be subdivided into four groups, each based on a specific type of nuclear reaction:

- In the (α, n) reactions an energetic alpha particle from an extraneous source interacts with a target nucleus to yield a spectrum of fast neutrons.
- In photonuclear or (γ, n) reactions, gamma rays are absorbed by nuclei which emit neutrons; the energy of the emitted neutron is determined by the difference between the photon energy and the neutron binding energy.
- In the fission reaction, spontaneous or induced, the nucleus of a fissionable element breaks up into two large fission fragments accompanied by the release of a large amount of energy and two or more neutrons.
- In charged-particle-induced neutron-yielding reactions accelerated protons, deuterons, or ions interact with a target isotope which leads to the emission of a neutron.

The yield, or the number of neutrons emitted per second, is the most important quantitative neutron source parameter. The specific neutron yield is defined as the number of neutrons emitted by the source per second per

curie* of the active substance contained in the source, or per unit of the current of accelerated charged particles incident on the target. The actual neutron source yield is usually somewhat smaller than the total number of neutrons produced in the source; some neutrons are absorbed in the source itself and in its protective casing.

Most neutron source reactions produce fast neutrons. Their energy depends upon the energetics of the reaction, the energy of the incident particle, and the angle of emission of the neutron relative to the angle of incidence of the particle. Less energetic or slow neutrons can be obtained by surrounding a source of fast neutrons by an appropriate moderator. The effect of the moderator on the characteristic energy spectrum of the source neutrons will depend on the thickness and the nature of the moderator.

Because of the angular dependence of neutron emission from certain neutron-producing reactions, as well as the asymmetry of neutron source construction, the spatial emission of neutrons from a given source cannot be assumed to be isotropic. The angular distribution of neutrons emitted by a source is therefore another parameter to consider in specific applications.

Each neutron source also emits a certain amount of gamma radiation. The intensity of this radiation is significantly

* The curie is a unit for measuring the activity of a radioactive isotope, equal to 3.7×10^{10} disintegrations per second.

different for neutron sources of different types, a factor that sometimes influences

the choice of a particular reaction for a specific application.

III. Neutron Generating Instruments

Neutron generating instruments fall into two specific categories, nuclear reactors and neutron generators. Most such instruments are large, stationary installations which depend on extensive extraneous electronic and structural equipment. Reactors are inherently bulky; the smallest of them weighs half a ton. A minimum amount of fissile material and moderator is required for their operation, and thick shields are needed to reduce the emitted radiation to safe levels. Neutron generators, however, do not have such limitations and can be designed as small, compact units.

A. NUCLEAR REACTORS

Nuclear reactors are powerful neutron sources. They are based on the controlled fission chain reaction of heavy nuclei, and can produce a large quantity of surplus neutrons for intense and prolonged irradiation of materials. Reactors can be built either for steady state or for pulsed operation modes; the latter is usually designed to produce short intense bursts of neutrons.

Aside from large power-producing or research reactors, small specialty reactors have been designed for specific industrial applications. Such small reactor sources are used for neutron radiography, transportable power supplies, and could ostensibly be used for other applications. A documented tabulation

of specialty reactors is given in Chapter V of this report.

B. NEUTRON GENERATORS

Neutron generators are charged-particle accelerators operating at energies which lead to neutron yielding reactions in a target. In most cases they impart the necessary energy to either electrons, protons, deuterons, or ions by accelerating them in an electric field.

Depending on the intensity of their yield and designed applications, the size of neutron generators can vary considerably. Sealed tube generators, designed for oil well logging, consist of cylinders a few feet long and less than a foot in diameter; those incorporated in large accelerator installations can exceed hundreds of feet in length and tens of feet in diameter.

Charged particle neutron generators normally employ one of three types of nuclear reactions:

- The interaction of accelerated deuterons with a tritium target
 $T + D \rightarrow {}^4\text{He} + n + 17.6 \text{ MeV}$
in which the neutron carries four-fifths of the reaction energy, i.e., 14.1 MeV,
- The interaction of accelerated deuterons with a deuterium target
 $D + D \rightarrow {}^3\text{He} + n + 3.2 \text{ MeV}$
in which the neutron carries off three-quarters of the reaction energy, i.e., 2.8 MeV,

- The photonuclear, or (γ, n), reactions in which accelerated electrons produce intense gamma rays by bremsstrahlung, and the subsequent interaction of these gamma rays to produce neutrons.

An alternate approach to impart the required energy to charged particles for the production of neutrons has been under development in recent years by a number

of laboratories. This type of device, called a coaxial plasma gun, consists of a plasma accelerator which converts stored magnetic energy into plasma energy; the plasma is subsequently collapsed by a radial magnetic field generating a short-lived, dense, high temperature plasma in which tritium and deuterium react to produce a burst of 14 MeV neutrons (GA71).

IV. Isotope Sources

A. FUNDAMENTAL PROPERTIES

Isotope sources of neutrons use isotopes, either singly or in combination, which undergo neutron-yielding nuclear reactions.

Although their neutron yield is normally low, not exceeding 10^8 neutrons per second (except for the Cf-252 spontaneous fission yield), isotope sources have a number of distinct advantages over the more elaborate reactor and accelerator sources. They are small, relatively simple to prepare, and easy to handle; furthermore, neutron isotope sources have stable yields, decaying predictably over periods ranging from months to hundreds of centuries.

All atomic nuclei, with the exception of the hydrogen atom, contain neutrons and should in principle be able to emit them. In almost all stable and radioactive nuclei, however, the protons and neutrons are firmly bonded by nuclear forces. Stable nuclei, therefore emit no neutrons without being artificially excited. A stable nucleus can emit a neutron only after absorbing energy exceeding the binding energy of the neutron in the

nucleus, which varies typically between 1.7 MeV and 20.6 MeV. In practice this is achieved by subjecting it to radiation emitted by naturally unstable or radioactive isotopes.

Radioactive isotopes disintegrate in five basic modes;

- alpha decay associated with the emission of an alpha particle,
- conversion of a proton into a neutron, a process which is accompanied by either positron emission or capture of an orbital electron,
- conversion of a neutron into a proton associated with beta decay accompanied by the emission of beta particles and internal conversion electrons,
- gamma decay associated with the emission of one or more gamma rays,
- spontaneous fission.

In addition, most decay processes via any of the modes described above are accompanied by the emission of x-rays or secondary gamma rays.

The only decay modes energetic enough to excite nuclei above the neutron emission threshold, as determined by the

neutron binding energy, are the alpha and gamma decay processes. Spontaneous fission, a natural neutron-producing process, will be considered separately in Section C.

B. (α, n) AND (γ, n) NEUTRON SOURCES

All (α, n) and (γ, n) isotope neutron sources consist of two elements, a radioactive isotope which undergoes either alpha or gamma decay, and a stable isotope whose cross-section for the (α, n) or (γ, n) reaction is high enough to yield an adequate source of neutrons.

The yield per unit time of a neutron isotope source, as well as its behavior as a function of time, depend on the rate at which the radioactive isotope decays. This rate of decay is characterized by a time constant known as the "decay constant" λ , and represents the probability that a nucleus will disintegrate by a particular decay mode within a given length of time. If a radioactive source consists of N nuclei then its activity, i.e., the total number of disintegrations per unit time, will be $N\lambda$. A more common parameter used to represent the time dependence of radioactive decay is the half-life, $T_{1/2}$. The half-life of a radioactive isotope, or the time required for one-half of the radioactive nuclei to decay, is related to the decay constant λ by

$$T_{1/2} = 0.693/\lambda .$$

Alpha-neutron sources have long been a common source of neutrons for laboratory use. In these sources, the neutrons are produced by the interaction of alpha particles with various target nuclei in

(α, n) reactions. The uranium, thorium and actinium decay chains contain numerous natural alpha-emitters. Daughter nuclei in these decay chains emit α particles with energies from 4 to 6 MeV. In addition a number of artificially produced heavy nuclei, which emit α particles in the same energy range, can similarly be used in (α, n) sources.

In an alpha-neutron source, an alpha-emitting substance is mixed thoroughly with a target material. In some cases, they may be combined as a chemical compound, or an alloy. The choice of the alpha emitter may, in any given case, depend on a variety of factors including alpha particle energy, the activity half-life, and cost of the emitter. As can be seen from Table 1, beryllium is the best material with regard to neutron yield and is almost always the target material selected for small portable (α, n) neutron sources.

The neutron yield is also affected by the proportion in which the alpha emitter and the target material are mixed. The (α, n) neutron yields given in Table 1 assume optimum mixing of the source and target materials and no absorption of alphas or of the emitted neutrons in the source itself. In practice such ideal conditions cannot be realized; the mixture is never perfect and there is always some absorption, both in the mixture and in the walls of the container. Also, the overall size of the source sometimes dictates the use of suboptimum proportions.

Photoneutron sources consist of an encapsulated gamma emitting isotope, or source mixture, surrounded by a layer of beryllium or deuterium oxide. Neutron emitting reactions induced by gamma

Table 1. Alpha-neutron source reactions and their characteristics.

Source	Half-life	Alpha energy (MeV)	Neutron energy (MeV)		Yield 10^6 neutron/sec α curie	References
			Max.	Average		
²¹⁰ Pb-Be (RaD-Be)	22 yr	3.72, 5.305	10.87	4.5-5.0	2.3-2.5	1, 2, 3, 4, 5
²⁰⁸ Po-Be	2.93 yr	5.11	10.71	(a)	(a)	4
²¹⁰ Po-Li	138.4 d	5.305	1.3-2.6	0.48	0.05-0.4	2, 4, 5, 6, 7
²¹⁰ Po-Be	138.4 d	5.305	10.87	4.2	2.3-3.0	1, 3, 4, 5, 6, 8
²¹⁰ Po-B	138.4 d	5.305	6.4	3.0	0.5-0.81	2, 4, 6, 7
²¹⁰ Po-C	138.4 d	5.305	7.5	(a)	0.004	3, 4, 8
²¹⁰ Po-O	138.4 d	5.305	(a)	(a)	0.0026	2, 3, 8
²¹⁰ Po- ¹⁸ O	138.4 d	5.305	4.3	2.3	1.1	2
²¹⁰ Po-F	138.4 d	5.305	2.8	1.4	0.15-0.444	2, 4, 5, 7
²¹⁰ Po-Na	138.4 d	5.305	4.45	(a)	0.04	5
²¹⁰ Po-Al	138.4 d	5.305	(a)	(a)	0.02-0.03	3, 6, 8
²²² Rn-Be	3.82 d	5.49	13.08	4.7	14.0-15.0	2, 5
²²⁶ Ra-Be	1620 yr	4.78(94), 4.60(6) (plus others)	13.08	3.9-4.7	10.0-17.1	1, 2, 4, 5, 6, 7
²²⁶ Ra-BeF ₄	1620 yr	4.78(94), 4.60(6) (plus others)	13.08	4.7	1.85-3.0	2, 5, 7
²²⁶ Ra-B	1620 yr	4.78(94), 4.60(6) (plus others)	(a)	(a)	7.0	5, 6
²²⁷ Ac-Be	21.8 yr	many(4.86-6.04)	12.79	4.0-4.7	15-26	1, 2, 3, 4, 5, 7
²²⁸ Th-Be (RdTh-Be)	1.91 yr	5.43(71), 5.34(28) (plus others)	(a)	(a)	17.0-20.0	1, 3, 4
²³² U-Be	72 yr	5.32(68), 5.27(32) (plus others)	(a)	(a)	22.0	1
²³⁸ Pu-Be	86.4 yr	5.50(72), 5.46(28)	11.3	5.0	2.2-4.0	1, 2, 7, 8
²³⁸ Pu-C	86.4 yr	5.50(72), 5.46(28)	7.4	(a)	0.005	8
²³⁸ Pu-O	86.4 yr	5.50(72), 5.46(28)	5.8	(a)	0.003	7, 8
²³⁸ Pu- ¹⁸ O	86.4 yr	5.50(72), 5.46(28)	(a)	(a)	(a)	9
²³⁸ Pu-F	86.4 yr	5.50(72), 5.46(28)	3.2	(a)	(a)	9
²³⁸ Pu-Al	86.4 yr	5.50(72), 5.46(28)	2.5	(a)	0.04	8
²³⁹ Pu-Be	24390 yr	5.16(88), 5.11(11)	10.74	4.5-5.0	1.5-2.2	1, 2, 3, 4, 5, 7, 9
²⁴⁰ Pu-Be	6580 yr	5.17(76), 5.12(24)	(a)	(a)	~1.7	7
²⁴¹ Am-Li	458 yr	5.49(85), 5.44(13)	(a)	(a)	0.04	7
²⁴¹ Am-Be	458 yr	5.49(85), 5.44(13)	11.5	5.0	2.2-2.7	1, 2, 3, 5, 7
²⁴¹ Am/ ²⁴² Cm-Be	458 yr/162.5 d	5.44-6.12	(a)	(a)	(a)	10
²⁴¹ Am-B	458 yr	5.49(85), 5.44(13)	(a)	(a)	0.5	7
²⁴¹ Am-F	458 yr	5.49(85), 5.44(13)	(a)	(a)	0.15	7
²⁴² Cm-Be	162.5 d	6.12(74), 6.07(26)	11.5	(a)	3.0-7.0	2, 7, 8
²⁴² Cm-C	162.5 d	6.12(74), 6.07(26)	8.0	(a)	0.01	8
²⁴² Cm-O	162.5 d	6.12(74), 6.07(26)	6.3	(a)	0.006	8
²⁴² Cm-Al	162.5 d	6.12(74), 6.07(26)	3.1	(a)	0.07	8
²⁴⁴ Cm-Be	17.6 yr	5.81(77), 5.77(23)	11.2	(a)	6.0	1, 7, 8
²⁴⁴ Cm-C	17.6 yr	5.81(77), 5.77(23)	7.6	(a)	0.008	8
²⁴⁴ Cm-O	17.6 yr	5.81(77), 5.77(23)	6.1	(a)	0.005	8
²⁴⁴ Cm-Be	17.6 yr	5.81(77), 5.77(23)	2.7	(a)	0.05	8
Mock Fission	138.4 d	(a)	10.87	1.6	0.4	5

(a) No information available.

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rays can take place if the energy of the gamma ray is greater than the binding energy of the neutrons in the target nucleus. This "threshold energy" is 1.64 MeV for beryllium, and 2.226 MeV for deuterium. In all other isotopes the threshold is over 5 MeV, eliminating them as target materials in (γ, n) sources.

There are two natural radioisotopes suitable for inducing (γ, n) reactions in either beryllium or deuterium. One of these is ^{214}Bi , a short lived daughter of ^{226}Ra , (half-life = 1620 years). The other is ^{208}Tl , daughter of ^{228}Ra (half-life = 6.7 years) and ^{228}Th (half-life = 1910 years). ^{226}Ra is ideal for making very stable standard neutron sources, but its yield is low. ^{228}Ra is seldom used because it is not generally available, but its daughter nucleus ^{228}Th is an excellent substitute as it can readily be produced by the neutron irradiation of ^{226}Ra in reactors.

A few artificially produced isotopes are suitable for use in photoneutron sources, but their half lives are rather short. Among these, ^{124}Sb is the only one commonly used. Its half-life is relatively long, its neutron yield is good, and high specific activities can be produced at a reasonable cost. ^{124}Sb is used only with beryllium since its gamma rays have energies below the threshold energy of deuterium.

The characteristics of photoneutron source reactions are listed in Table 2. An attempt has been made to compile as complete a listing as possible including not only commonly used isotope sources (the most important of which are framed),

but also those which can potentially be used. The half-lives and the energies of individual gamma rays were obtained from the "Table of Isotopes" (LE67); wherever possible, the relative abundance of each gamma ray is given (in percent) in parenthesis following the energy.

The neutron yield for each source is listed separately for beryllium (Be) and deuterium (D) targets; it includes measured or calculated neutron energy and the neutron yields. Neutron yields are given in neutrons per second per curie source strength; those underlined represent values which have consistently been reported in the literature (SO62, JA68). The other values, followed by an asterisk (*), are based on recently published calculated values by Beyster and Kull (BE70). These values, however, were calculated for a specific source design, and differ from the "standard neutron yields" usually quoted in the literature.

The "standard neutron yield" is defined as the number of neutrons per second emitted by one gram of beryllium or deuterium placed at one centimeter from a one curie source. In practice the target material surrounds the gamma emitting material. The actual yield of a given source is obtained by multiplying the standard yield by $23t$ for beryllium and $13t$ for deuterium, t being the thickness of the target in centimeters, in order to account for source geometry and secondary nuclear processes in the source. To convert Beyster's values to the standard yields his values, calculated for a source in which $t = 0.79$ cm, were divided by a factor of 18.17 in the case of Be and 7.9 in the case of D.

Table 2. Photoneutron source reactions and their characteristics.

Source	Half-life	Gamma energies above Be threshold (MeV)	Be Target		D Target	
			Average neutron energy (MeV)	Standard ^a neutron yield 10 ⁵ neutron/sec curie	Average neutron energy (MeV)	Standard ^a neutron yield 10 ⁵ neutron/sec curie
²⁴ Na	15.0 hr	2.754(100)	0.83 ^c 0.80 ^d	1.3/1.08 ^b	0.22 ^{c,d}	2.7/2.13 ^b
⁴⁸ V	16.1 d	2.25(3)	0.55	<0.45 ^b	(e)	(e)
⁵⁶ Mn	2.576 hr	1.811(29.3), 2.11 (15.5), 2.52(1.1), 2.66(0.7), 2.95(0.5), 3.37(0.2)	0.15 ^{c,d} 0.30 ^d	0.3	0.22 ^c	0.03
⁵⁶ Co	77.3d	1.76(15), 2.02(11), 2.60(17), 3.26(12)	<1.5	0.63 ^b	<0.55	0.63 ^b
⁵⁷ Ni	36.0 hr	1.89(14)	0.23	0.18 ^b	—	(None)
⁷² Ga	14.1 hr	1.86(5), 2.20(26), 2.5(20)	0.27 ^c	0.5/0.45 ^b	0.13 ^c	0.6/0.32 ^b
⁷² As	26.0 hr	1.68, 1.75, 1.92, 2.08, 2.20, 2.24, 2.32, 2.51, 2.63, 2.76, 2.91, 3.0, 3.74	<1.9	(Small)	<0.75	(Small)
⁷⁶ As	26.5 hr	1.789(0.3), 2.1(0.9)	0.29	<0.045 ^b	—	(None)
⁸⁶ Y	14.6 hr	1.857(18), 1.925(24)	0.27	0.225 ^b	—	(None)
⁸⁸ Y	108.1 d	1.836(99), 2.76(0.46)	0.158 ^f 0.22	1.0/0.53 ^b	0.27	0.03
¹⁰⁶ Ru	367 d	>1.76(0.76) from ¹⁰⁶ Rh daughter	(e)	(e)	0.22	0.08 ^b
¹⁰⁰ Rh	20 h	1.94(10), 2.37(39)	0.28	0.15	(e)	(e)
^{116m} In	53.9 m	2.111(20)	<0.15 ^d 0.30	0.08	—	(None)
¹²⁵ Sn	9.4 d	1.97(0.6), 2.23(0.05)	0.29	(Small)	(e)	(e)
¹²⁴ Sb	60.4 d	1.692(50), 2.088(7)	0.035 ^f 0.024 ^{c,f}	1.9/1.53 ^b	—	(None)
^{119m} Te	4.68 d	2.09(4)	0.41	0.0225 ^b	—	(None)
¹²⁴ I	4.15 d	1.69(14), 2.09(2), 2.26(1.5)	0.05	0.45 ^b	(e)	(e)
¹⁴⁰ La	40.2 d	2.52(3)	0.62 ^c	0.027/0.027 ^b	0.13 ^c 0.15 ^f	0.08/0.047 ^b
¹⁴⁴ Ce	284 d	2.186(0.7) (from ¹⁴⁴ Pr daughter)	0.51	<0.045 ^b	—	(None)
¹⁸⁸ Ir	41.5 hr	>1.688(35) complex >2.350(0.35)	0.37	0.135 ^b	(e)	(e)
¹⁹⁴ Au	39.5 hr	1.887(4), 2.044(4)	(e)	(e)	—	(None)
²⁰⁵ Bi	15.31 d	1.766(27), 1.778(3), 1.864(8), 1.906(2), 2.61(2)	<0.25	0.675 ^b	(e)	(e)
²⁰⁶ Bi	6.243 d	1.72(36)	0.08	0.855 ^b	—	(None)
²⁰⁷ Bi	30 yr	1.771(9)	0.120	0.135 ^b	—	(None)
²⁰⁸ Bi	2.68 × 10 ⁵ yr	2.614(100)	(e)	(e)	0.20	1.82 ^b
²¹¹ Rn	15 hr	1.81(1)	0.15	(Small)	—	(None)
²²⁸ Ra (^{MsThI}) ^g	6.7 yr	2.615 MeV gamma from ²⁰⁸ Tl daughter in Th decay chain	0.827 ^f	0.35/0.72 ^b	0.197 ^f	0.95/1.1 ^b
²²⁸ Th	1.91 yr	E _γ = 1.73, 1.76, 1.85, 2.12, 2.20, 2.45 MeV from ²¹⁴ Bi daughter in decay chain	<0.670	0.3/0.45 ^b	0.12	0.01/0.063 ^b
²²⁶ Ra ^g	1620 yr					

Comments

^aThe standard neutron yields are the number of neutrons per second emitted by one gram of beryllium or heavy water placed at one centimeter from a one-curie source. In practice, the source is surrounded by the target, and the approximate yield can be obtained by multiplying the above yields by 23t for beryllium and by 13t for heavy water, t being the thickness of the target in centimeters.

^bValues given in Reference (BE70) converted to standard neutron yields (see text).

^cThe neutron energies were determined by measuring the scattering cross section in paraffin (hydrogen) which is a known function of energy. (SO62)

^dThe neutron energies were determined from observing head-on proton collisions in a hydrogen-filled cloud chamber. (SO62)

^eNo information available.

^fThe neutron energies were determined from maximum pulse heights of recoil protons in a hydrogen-filled proportional counter. (SO62)

^g²²⁸Ra (^{MsThI}) and ²²⁶Ra are assumed to be in equilibrium with their decay products. The photon and neutron yields are based on the number of disintegrations of the parent source.

C. FISSION NEUTRON SOURCES

Fission, whether spontaneous or induced, is probably the most important neutron yielding process. Heavy nuclei subject to the fission process most often split into two fragments, with the simultaneous emission of several neutrons and the release of about 200 MeV of energy. Although induced fission can be initiated not only by neutron bombardment and gamma irradiation but also by the impact of energetic protons, alpha particles or ions, and by capture of mesons, the actual fissioning process is the same in all cases: conversion into a compound nucleus, followed by fission. Spontaneous fission, however, takes place without external excitation. All nuclei of atomic number larger than 90 are energetically unstable to decay by fission, but the probability for spontaneous fission of naturally occurring heavy nuclei in the ground state is very small. The process itself takes place as a result of a random redistribution of energy within the nucleus caused by the vibrations of the individual constituents of the nucleus. The result of this process, however, does not differ substantially from induced fission.

Induced fission is the process basic to the operation of nuclear reactors. With the exception of applications in experimental nuclear physics work, this process is not usually applicable to the design of neutron sources for use outside the laboratory. Spontaneous fission, on the other hand, offers distinct advantages in its use as a practical source of neutrons.

The selection of specific isotopes for neutron source application is primarily determined by their spontaneous fission decay constant and their total half-life. While it is desirable to have a reasonably high yield of neutrons from a given isotope, its half-life must be long enough to guarantee a reasonably constant yield and longevity of the source. It must also be borne in mind that the total half-life for a given isotope is usually considerably smaller than that for spontaneous fission. This implies that the nuclide of interest decays faster by its basic decay mode, usually by alpha emission, than by spontaneous fission. Thus it can be seen from the tabulation given in Table 3 that the heavier elements are impractical as neutron sources. Even though their indicated neutron yields are extremely high, their total half-lives are on the order of days or even hours.

A number of isotopes listed in Table 3 could in principle qualify, on the basis of half-life, as neutron sources for practical applications. The neutron yield of all naturally occurring isotopes (identified in the table) is comparatively low, however, while most of the artificially-produced isotopes can be produced in limited quantities only. ^{252}Cf , with a neutron yield of 2.32×10^{12} neutrons per second per gram of isotope and a total half-life of 2.65 years, is the only one of the known nuclides whose combination of half-lives and physical properties enable it to compete favorably with those of the (α, n) and (γ, n) isotope neutron sources described in the previous section.

Table 3. Specific activity and neutron yield of spontaneously fissioning nuclides.

Source	Total half-life ^a	Spontaneous fission half-life ^a	Spontaneous fission activity g sec	$\bar{\nu}$ neutrons fission	Yield neutrons g sec	Comments
²³⁰ Th	8×10^4 hr	1.5×10^{17} yr	3.84×10^{-5}	1.24	$\leq 4.76 \times 10^{-5}$	(b) (c)
²³² Th	1.41×10^{10} yr	10^{21} yr	5.72×10^{-8}	2.6	1.49×10^{-7}	(c)
²³² U	72 yr	$\approx 8 \times 10^{13}$ yr	7.15×10^{-1}	—	~2.15	(d)
²³⁴ U	2.47×10^5 yr	2×10^{16} yr	2.83×10^{-3}	1.63	4.61×10^{-3}	(b)
²³⁵ U	7.1×10^8 yr	1.9×10^{17} yr	2.97×10^{-4}	~2.5	7.43×10^{-4}	(c)
²³⁶ U	2.39×10^7 yr	2×10^{16} yr	2.81×10^{-3}	1.58	4.44×10^{-3}	(b)
²³⁸ U	4.51×10^9 yr	6.5×10^{15} yr	8.55×10^{-3}	2.1/2.3	1.8×10^{-2}	(b) (c)
²³⁷ Np	2.14×10^6 yr	10^{18} yr	5.59×10^{-5}	—	1.7×10^{-4}	(d)
²³⁶ Pu	2.85 yr	3.5×10^9 yr	1.61×10^4	2.2/2.3	3.55×10^4	(b)
²³⁸ Pu	86.4 yr	4.9×10^{10} yr	1.13×10^3	2.33	2.64×10^3	
²³⁹ Pu	2.44×10^4 yr	5.5×10^{15} yr	1.01×10^{-2}	2.28	2.30×10^{-2}	
²⁴⁰ Pu	6.58×10^3 yr	1.40×10^{11} yr	3.94×10^2	2.12	8.34×10^2	
²⁴² Pu	3.79×10^5 yr	7×10^{10} yr	7.82×10^2	2.18/2.26	1.80×10^3	(b)
²⁴⁴ Pu	7.6×10^7 yr	2.5×10^{10} yr	2.17×10^3	—	$\sim 6.5 \times 10^3$	(d)
²⁴¹ Am	4.58×10^2 yr	2×10^{14} yr	2.75×10^{-1}	3.14	8.64×10^{-1}	(b)
²⁴⁰ Cm	26.8 d	7.9×10^5 yr	6.98×10^7	—	$\sim 2.1 \times 10^8$	(d)
²⁴² Cm	162.5 d	7.2×10^6 yr	7.59×10^6	2.49/2.65	1.8×10^7	(b)
²⁴⁴ Cm	17.6 yr	1.31×10^7 yr	4.15×10^6	2.81	1.17×10^7	
²⁴⁶ Cm	5.5×10^3 yr	1.7×10^7 yr	3.16×10^6	—	$\sim 9.5 \times 10^6$	(d)
²⁴⁸ Cm	4.7×10^5 yr	4.7×10^5 yr	1.14×10^6	—	$\sim 3.4 \times 10^6$	(d)
²⁵⁰ Cm	1.7×10^4 yr	1.7×10^4 yr	3.11×10^9	—	$\sim 9.3 \times 10^9$	(d) (f)
²⁴⁹ Bk	314 d	6×10^8 yr	8.88×10^4	3.72	3.30×10^5	(e)
²⁴⁶ Cf	35.7 hr	2.1×10^3 yr	2.57×10^{10}	2.92	7.50×10^{10}	
²⁴⁸ Cf	350 d	1.5×10^4 yr	3.57×10^9	—	1.1×10^{10}	(d)
²⁴⁹ Cf	360 yr	1.5×10^9 yr	3.56×10^4	—	1.1×10^5	(d)
²⁵⁰ Cf	13.2 yr	1.7×10^4 yr	3.11×10^9	—	$\sim 9.3 \times 10^9$	(d)
²⁵² Cf	2.65 yr	8.5×10^1 yr	6.17×10^{11}	3.76	2.32×10^{12}	
²⁵³ Es	20.47 d	6.4×10^5 yr	8.17×10^7	—	$\sim 2.4 \times 10^8$	(d)
²⁵⁴ Es	276 d	7.5×10^5 yr	7.44×10^7	—	$\sim 2.2 \times 10^8$	(d)
^{254m} Es	39.3 hr	>10 yr	$< 5.2 \times 10^{12}$	—	$> 1.6 \times 10^{13}$	(d) (e)
²⁵⁵ Es	38.3 d	>170 yr	$< 3.04 \times 10^{11}$	—	$> 9.1 \times 10^{11}$	(d) (e)
²⁵² Fm	22.7 hr	>8 yr	6.57×10^{12}	—	$\sim 2.0 \times 10^{13}$	(d)
²⁵⁴ Fm	3.24 hr	230 d	8.25×10^{13}	4.05	3.34×10^{14}	
²⁵⁵ Fm	20.1 hr	10^4 yr	5.19×10^9	—	$\sim 1.6 \times 10^{10}$	(d)
²⁵⁶ Fm	2.7 hr	2.7 hr	1.68×10^{17}	—	$\sim 5.0 \times 10^{17}$	(d) (f)
²⁵⁷ Fm	80 d	94 yr	5.48×10^{11}	—	$\sim 1.6 \times 10^{12}$	(d)

Comments

^aHalf-lives are taken from Ref. (LE67).

^bAverage number of neutrons per fission from Ref. (BA69).

^cNaturally-occurring isotope.

^dAverage number of neutrons per fission assumed to be 3.0.

^ePrimary mode of decay is by β^- .

^fOnly mode of decay is by spontaneous fission.

V. Neutron Source Uses and Applications

Neutron sources of all types have a wide variety of applications in research and industry, and their widespread use leads to their presence in a multitude of locations. Some of these are:

- Remote land or sea-based sites of geophysical, hydrological and mineral explorations.
- Industrial sites related to coal, steel, chemicals, petroleum, explosives and aircraft production.
- Laboratories involved in biological and space research and pollution control.
- Hospitals, medical facilities and educational centers.
- Sites or mobile units, for fissile material assays.
- Sites of military operations.

The most common general fields of applications of neutron sources can be summarized under the following ten headings:

1. Industrial quality control
2. Chemical analysis
3. Geophysical exploration
4. Power generation
5. Oil well logging
6. Radiation effects studies
7. Medical therapy
8. Education and research
9. Radioisotope production
10. Fissile material assay

Documented applications of each type of neutron source considered in Chapters III and IV of this report and their possible locations are summarized in the three sections below.

A. REACTOR APPLICATIONS

Nuclear reactors constitute the most copious of all neutron sources. Although they are principally used in large power plants for the production of electricity, a number of small-scale specialty reactors have been developed in the course of the last decade which can be considered in context of the neutron source definition used in this report. Table 4 contains a representative sample of such reactors; it should not be considered to be complete, however.

B. NEUTRON GENERATOR APPLICATIONS

High voltage particle accelerators used in the production of neutrons have two distinct advantages over isotopic neutron sources. Their neutron yields are considerably larger, and the energy of the produced neutrons is monochromatic. Another important distinction of accelerator type neutron generators is that they can be switched on and off, reducing operation costs and improving transport safety for off-site applications.

There are three basic types of neutron producing accelerators: potential drop accelerators, linear accelerators and cyclotrons. Most of these instruments are large stationary installations located at nuclear research centers. Small neutron generators, amenable to off-site or remote applications, are restricted primarily to potential drop accelerators. These can be classified into pulsed tube accelerators, pinch plasma focus acceler-

Table 4. Small specialty reactor applications.

Reactor description	Application	Reference
Triga-Neutrovision reactor has operating power level of 100 kW and provides a neutron source flux of 3.5×10^{12} neutrons per cm^2 sec.	Industrial radiography.	(SC71)
Small French pulsed reactor with uranyl nitrate core and BeO reflector produces 10^5 fissions per second at 30 kW peak pulse power. Yields 3×10^9 thermal neutrons per cm^2 per pulse.	Radiation effects, research.	(FA71)
US transportable reactor power plants. Pressurized-water type uses compact core of UO_2 -stainless steel cermet fuel. Four operational units in operation: SM-1A(20 MW), PM-1(9.4 MW), PM-2A(10 MW), PM-3A(9.5 MW). Typical plant consists of 18 modules, weighing 30,000 lb each.	Power and heat production at remote locations.	(RO64)
USSR transportable nuclear power plant TES-3. Water moderated heterogeneous 11 MW, water cooled reactor. Built on self-powered half-tracked vehicles. Total weight of power plant is 310 metric tons.	Power and heat production at remote locations.	(SI64)
SNAP-10A reactor for space application, representative of the US program. Direct conversion unit produces 500 W and weighs 950 lb.	Auxiliary power for space	(DI64)
USSR high-temperature, direct conversion reactor "Romashka." Rated at 40 kW(th). External neutron leakage flux 3×10^{11} neutrons per cm^2 sec.	Auxiliary power for space application.	(MI64)
ML-1 water-moderated gas-cooled reactor driving a gas turbine. US military mobile 3.0 MW power plant. Consists of four units, with total weight of 81,500 lb.	Auxiliary power for remote locations.	(ID62)

ators, Cockroft-Walton accelerators, and the Van de Graaff or Dynamatron accelerators. The neutron yields from these instruments range from 10^{11} to 10^{13} neutrons per second.

Table 5 lists the major areas of applications of neutron generating accelerators. A more detailed tabulation of actual documented applications is given in Table 6.

C. ISOTOPE NEUTRON SOURCES

At present isotopic neutron sources are made from about 20 radioisotopes, and are adaptable to a variety of applications. Because of their long life, ^{241}Am -Be and ^{238}Pu -Be sources widely used in instruments and other applications which require a constant low neutron output. On the other hand,

Table 5. Uses of neutron generators
(MO71).

A. Nuclear Science and Engineering	
1.	Nuclear structure research
2.	Neutron physics research
3.	Reactor physics engineering
4.	Weapons research
5.	Teaching and training
B. Neutron Diagnostics	
1.	Neutron logging
2.	Industrial process control
3.	Neutron radiography
4.	Construction
5.	Water resources
6.	Nuclear safeguards.
C. Radiation Effects	
1.	Research in chemistry, biology
2.	Activation analysis
3.	Isotope production
4.	Radiation simulation
5.	Weapons effects
6.	Neutron radiotherapy
D. Atomic and Solid-State Physics	
1.	Neutron spectroscopy
2.	Impurity modification
3.	Solid-state research and development
4.	Structure and bulk properties

where higher neutron yield is needed, $^{227}\text{Ac-Be}$, $^{210}\text{Po-Be}$, $^{228}\text{Th-Be}$, and $^{242}\text{Cm-Be}$ are usually used. Photoneutron sources and some newly designed (α, n) sources have provisions for switching the neutron output on and off.

In general, because of their size, minimum maintenance requirements, and variety of yields, isotopic neutron sources are versatile tools widely used in the laboratory and in field applications. Table 7 shows a representative sample of isotope neutron source applications.

D. SPONTANEOUS FISSION SOURCES

Of all spontaneously fissioning isotopes (see Table 3) ^{252}Cf , because of its

high yield and long half-life, has been used almost uniquely as a spontaneous fission neutron source. A tabulation of its various applications, classified according to its neutronic properties, is shown in Table 8. Some documented applications appear in Table 9. Additional information as to the characteristics and applications of ^{252}Cf can be found in "Californium-252 Progress," a monthly journal published by the U.S. Atomic Energy Commission.

E. INCIDENTAL NEUTRON SOURCES

In addition to sources specifically designed to produce neutrons there are, in other fields of applied nuclear technology, possible conditions under which neutrons appear as a side product. Examples of such incidental sources of neutrons can be found for instance, in currently used or proposed auxiliary power generating devices.

A number of neutron emitters and alpha emitters currently used in isotope power generators constitute either actual or potential sources of neutrons; ^{238}Pu , ^{242}Cm , and ^{244}Cm have a substantial spontaneous fission yields. The amount of the radioisotope used in these power generators varies according to the needed power output, from fractions of a gram of ^{238}Pu in a small micro-watt generator (DU66A) to 100 cc of ^{238}Pu in the form of its oxide or carbide for a 50-watt thermionic auxiliary power generator proposed in France (CL66). In the latter case, both the oxygen and the carbon can also yield neutrons via the (α, n) reaction induced by the ^{238}Pu alpha particles.

Table 6. Neutron generator applications.

Application	Instrument or technique	References
Industrial activation analysis	Sealed tube neutron generator to analyze nitrogen content in explosive propellants and high explosive materials, via the (n, 2n) reaction in N-14.	(SE71)
Industrial activation analysis	Application of neutron generators to radiometric methods in industrial chemical analysis—Copper and cadmium content in ores.	(FL65)
Industrial radiography	Use of a high yield neutron generator, producing 10^{11} neutrons per sec, in a thermal neutron television system.	(KA68)
Oil well logging	Application of the Soviet UNG-2 tube accelerator to geophysical exploration.	(IV68)
Radiation effects	Use of a dense plasma focus device as an intense pulsed 14 MeV neutron source.	(GA71)
Radiation effects studies (biological)	3 MV accelerator producing 14 MeV neutrons at more than 10^{11} n/sec.	(MA66)
Medical therapy (cancer)	Baldock neutron generator tube.	(MO67)
Fissile material assay	Use of a 200 kV positive ion accelerator for active neutron interrogation and assay of fissionable materials. In use in the Mobile Nondestructive Assay Laboratory by LASL.	(DE71)

Table 7. Isotope neutron source applications.

Applications	Technique	References
Industrial quality control	Measurement of density and water content of liquids transported in pipelines.	(KO66)
Industrial quality control	Automatic control and regulation of the humidity of a sinter charge.	(BE66)
Industrial quality control	Application of activation analysis with neutron sources to problems related to environmental pollution.	(LE71)
Chemical analysis	Detection of chemical elements by neutron activation with an $^{241}\text{Am}/^{242}\text{Cm}(\text{Be})$ neutron source.	(WI67)
Geophysical exploration	Portable radioactive snow gauge to monitor snow accumulation and snowmelt.	(SM66)
Geophysical explorations	Measurement of soil moisture in the field by neutron moderation and scattering.	(LO67, TO69)
Oil well logging	Geological and geophysical applications of isotope sources for the measurement of rock porosity.	(AU71)
Nuclear safeguards	Nuclear material assay and non-destructive testing.	(BE70, ME71, KU71)

Table 8. Uses of ^{252}Cf .

<p>A. Neutron Emission</p> <ol style="list-style-type: none"> 1. Standard fissions <ol style="list-style-type: none"> a. Fission studies b. Fission product damage c. Instrument calibration 2. Heat source 3. Target material <ol style="list-style-type: none"> a. New nuclide production 4. Standard neutron source <ol style="list-style-type: none"> a. Reactor physics b. Reactor startup c. Neutron damage d. Instrument calibration 5. Removal and redistribution <ol style="list-style-type: none"> a. Blackness meters b. Civil effects studies c. Shielding studies <p>B. Neutron Reactions - Scattering</p> <ol style="list-style-type: none"> 1. Well logging 2. Moisture meters 3. Light element measurements 4. Neutron radiography 5. Neutron diffraction <p>C. Neutron Reactions - Capture/Activation Analysis</p> <ol style="list-style-type: none"> 1. Ultra high sensitivity analysis <ol style="list-style-type: none"> a. Forensic b. Trace elements c. Purity control 	<ol style="list-style-type: none"> 2. Minerals and mining <ol style="list-style-type: none"> a. Bore-hole logging b. Mineral explorations c. Ore sorting 3. Process control <ol style="list-style-type: none"> a. On-line/on-stream analysis b. Raw material sorting c. Quality control d. Waste monitoring e. Assay of fissionable materials (safeguards) <p>D. Nuclide and Particle Production</p> <ol style="list-style-type: none"> 1. Chemical reaction initiation 2. Tumor treatment <p>E. Stable Isotope Production</p> <ol style="list-style-type: none"> 1. Semiconductor doping <p>F. Radioisotope Production</p> <ol style="list-style-type: none"> 1. Medical tracers <ol style="list-style-type: none"> a. Research b. Diagnosis c. Treatment 2. Scientific tracers <ol style="list-style-type: none"> a. Biological studies b. Chemical studies c. Metallurgical studies 3. Industrial tracers <ol style="list-style-type: none"> a. Meteorology and pollution b. Mixing and materials transport c. Flow and leak measurements
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Alpha emitting isotopes are commonly used in auxiliary electric power generators for satellite and space applications (CO66, JO66, SQ66, MO66). ^{238}Pu and ^{242}Cm which are two of the most commonly used isotopes, and ^{244}Cm which has also been proposed for such applications (CO66), have a considerable spontaneous fission neutron yield. A number of such devices using neutron yielding isotopes are listed in Table 10. The neutron yield from

spontaneous fission for these devices listed in Table 10 can be seen to be quite significant and are comparable in their intensity to (α, n) and (γ, n) isotopic neutron sources. A more complete descriptive list of auxiliary power generating devices can be found in reference (LA70).

Other strong alpha emitters commonly used in (α, n) sources, such as ^{210}Po , ^{227}Ac , and ^{228}Th , have been proposed for use in isotopic power generators as

Table 9. ^{252}Cf neutron source applications.

Application	Technique	References
Industrial process control, "on stream."	Neutron activation analysis applied to ores in solution.	(RH71, DU71A)
Industrial process control	Neutron activation analysis of steel for manganese content.	(AR71)
Industrial process control	Determination of sulfur content in metallurgical coal using radioactive capture.	(PA71B)
Industrial process control	Neutron radiography using ^{252}Cf for nondestructive testing aircraft components.	(DU71B)
Industrial process control	Activation analysis in pollution control.	(LE71)
Geophysical exploration	Truck-mounted borehole source for high resolution measurements of neutron-induced gamma rays.	(TA71)
Geophysical exploration	Underwater mineral content analysis with a Cf-252 source. Source can be located on board ship or underwater.	(NO71, PE71)
Geophysical explorations	Determination of porosity, salinity and gas content in formation surrounding a borehole.	(PA71A)
Geophysical exploration	Neutron logging of aquifers and applications of moisture gauges.	(FE71)
Oceanography and space application	Neutron activation of sea-floor and extraterrestrial planetary surface analysis.	(PE71)
Space applications	Power sources, elemental analysis experiments, spectrometer calibration.	(TR71)
Medical therapy	Radiotherapy with implantable ^{252}Cf needles.	(WR67)
Nuclear material safeguards	Nondestructive assay of fissionable materials in conjunction with the Safeguards program.	(FO71)
Military application	Explosive mine detection by means of neutron-induced gamma rays.	(MY71)

well (DO66, GI66, VO64). In conjunction with low atomic weight materials used as structural or functional elements in such generators, these energetic alpha particles could be very effective, although not necessarily desired, sources of fast neutrons. In particular, the proposed use of beryllium as radiator material of a thermoelectric generator

powered by an ^{227}Ac isotope source (ZA66) would be a potential source of neutrons.

Dynamic isotope power generators are a hybrid of a nuclear reactor and isotopic generator, using the heat from a radioisotope source to circulate a working fluid which operates a turbine. One such generator (NE66), uses a ^{210}Po or ^{242}Cm heat source with a

Table 10. Neutron emitting isotopic auxiliary power generating devices.

Designation	Country	Isotope	Activity (α curies)	Neutrons from S.F. ^a (neutrons/sec)	Applications
SNAP-3B7	US	^{238}Pu	1600	3.1×10^5	Transit satellites
SNAP-3B8	US	^{238}Pu	1600	3.1×10^5	Transit satellites
SNAP-9A	US	^{238}Pu	17,000	3.3×10^6	Navigation satellites
SNAP-11-1	US	^{242}Cm	12,480	6.8×10^8	Surveyor satellites
SNAP-11-2	US	^{242}Cm	20,400	1.1×10^9	Satellite
SNAP-13	US	^{242}Cm	—	—	Demonstration
SNAP-15A/B/C	US	^{238}Pu	2 - 200	$<4 \times 10^4$	Terrestrial control system
SNAP-19	US	^{238}Pu	20,000	3.9×10^6	Nimbus satellite
SNAP-25	US	^{238}Pu	—	—	Not used
SNAP-27	US	^{210}Po	5,000	$\sim 10^6$	Apollo
SNAP-29	US	^{238}Pu	—	—	Satellite
Pace-Maker	US	^{238}Pu (oxide)	3.5	6.8×10^2	Cardiac stimulation
Isomite	US	^{238}Pu	4 - 1000	$<1.9 \times 10^5$	Industry (many)
STEP	US	^{238}Pu	—	—	Underwater, land, space
Gipsie	French	^{238}Pu	2.5	4.8×10^2	Cardiac stimulation
IET	Euratom	^{242}Cm	1300	7×10^7	Demonstration
MIG 67	USSR	^{238}Pu	620	1.2×10^5	Meteorological station
Prototyp 5	USSR	^{210}Po	10,000	—	Space
Prototyp 6	USSR	^{210}Po	10,000	—	Space
Prototyp 7	USSR	^{210}Po	7,700	—	Space

^aNeutron emission rate from spontaneous fission (S.F.) of the isotope material of the generator. These values do not include possible (α, n) neutron yield within the generator. The neutron production could be a factor of 16 higher than spontaneous fission alone in normal ^{238}Pu oxide source material. (MU69).

liquid metal (e.g., Li or Na) working fluid. A number of such proposed devices

(DU66B) can also be considered potential neutron sources.

VI. Natural Background Neutron Levels

Natural background radiation on the earth's surface is the product of two different mechanisms, namely, interaction of cosmic rays with the atmosphere, and the natural decay of radioactive isotopes in the earth's crust. Both of these components are sources of neutrons, the cosmic rays being by far the more important of the two.

Cosmic rays entering the atmosphere interact with air nuclei to form protons, neutrons, mesons and other particles.

Some of these secondary particles possess enough energy to cause further disintegrations and create cascades of electrons and photons. The major fraction of cosmic-ray-produced neutrons originates from the neutron evaporation of excited nuclei produced by high-energy nuclear interactions. As these neutrons diffuse to lower levels in the atmosphere, they are degraded in energy and absorbed until their total population reaches an equilibrium condition. At sea level this

background neutron population is distributed in energy between thermal (0.025 eV) and 10 MeV; 50% have an energy above 0.1 MeV, and less than 15% have energies below 0.4 eV (YA66).

The rate of neutron production in the atmosphere due to cosmic radiation varies significantly with latitude and altitude. For instance, both fast and slow neutron detection rates show an increase of about 600% from the generation rate at the equator to that at the poles (SA68), and the rate of neutron production is approximately 10 times higher at 10,000 ft altitude than it is at sea level (YA66). These variations are illustrated in Table 11 which shows some experimentally determined cosmic-ray-induced neutron production levels. Table 12 gives the measured values of the neutron flux densities, both at sea level and at 10,000 ft altitude, for four energy groups.

Neutrons from the natural radioactivity of the earth's crust originate from two sources: (α , n) reactions in light elements and spontaneous fission of heavy nuclides. A large fraction of naturally occurring radioactive isotopes in the earth's crust decay by emitting energetic alpha particles. As was shown in Chapter IV alpha particles react with a number of light elements to produce neutrons. Since the earth's crust is primarily composed of light elements, oxygen (64.4 wt%), silicon (27.5 wt%) and aluminum (8.1 wt%), a certain level of neutron production is to be expected.

Based on calculations which assumed an average (α , n) yield of 75 neutrons from aluminum per 10^8 alpha particles from ^{210}Po , and a fractional composition of 3 ppm ^{238}U and 11 ppm ^{232}Th in the earth's crust, it has been estimated that the (α , n) neutron production was 2.1×10^{-7} neutrons per gram-second in sand, and

Table 11. Natural neutron production levels.
(All values are given in neutrons/second per 100 kg.)

	Latitude	Elevation ^a			
		Sea level	1100 ft	7,050 ft	10,600 ft
<u>Due to cosmic radiation</u>					
A. Neutron production in water (experimental results)	33° North	—	—	14.9 (GO69)	—
	37° North	—	3.0 (GO69)	—	—
	44° North	1.85 (YA66)	—	—	12.8 (YA66)
	56° North	3.7 (GO69)	—	—	—
B. Neutron production in air at 44° N, scaled from experimental results in water, given above		2.0 (YA66)	—	—	14.1 (YA66)
C. Average neutron production at the earth's surface		2.54 (FE68)	—	—	—
<u>Due to earth's radioactivity</u>					
A. Production in sand		0.025 (FE68)			
B. Production in granite		0.048 (FE68)			

^aAll reported measurements were made at the surface of the earth.

Table 12. Measured neutron flux densities on the earth's surface (YA66).

Neutron energies eV	At sea level ^a (44°N) 10 ⁻³ n/cm ² /sec	At 10,000 ft elevation ^a (44°N) 10 ⁻³ n/cm ² /sec
Thermal	1.07	12
0.4 - 10 ⁵	2.9	38
10 ⁵ - 10 ⁶	1.6	19
10 ⁶ - 10 ⁷	1.7	17

^aAt the earth's surface.

4.3×10^{-7} neutrons per gram-second in granite (FE68). The spontaneous fission component of natural neutron production,

which is primarily due to the spontaneous disintegration of ²³⁸U, has been estimated at 0.44×10^{-7} neutrons per gram-second (FE68).

It can readily be seen from Table 11, which gives the total neutron production in sand and granite-type soil, that the ground component contributes only approximately 1% of the total neutron background, and can therefore be ignored in the overall background neutron flux densities given in Table 12.

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