Californium-252 as a Neutron Source for BNCT

5

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5.1 Physical Properties of Californium-252

In November 1952, the isotope Cf-252 was discovered in the debris from the MIKE thermonuclear test at Enewetak [1]. Early investigations of its properties indicated a half-life of between 2 and 3 years (actually 2.645 years) and significant branching fractions for decay by spontaneous fission (SF), making Cf-252 an especially good and compact source of neutrons. Due to its availability in macroscopic quantities, Cf-252 has been one of the most extensively studied transplutonium isotopes. Most of the effort has been directed at understanding the spontaneous fission properties, some of which are summarised in Table 5.1. These properties make Cf-252 one of the most useful neutron emitters out of all the ~3,000 known radionuclides. Though isotopes such as Cf-254 and Md-260 have higher rates of spontaneous fission, their half-lives are too short, i.e. weeks, to permit large-scale fabrication. The majority,

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Table 5.1 Decay and spontaneous fission properties of Californium 252 [3–5]

Half-life	2.645 years
Specific activity	536.3 Ci/g
Decay mode	α (96.908 %), SF (3.092 %)
Neutron multiplicity	3.768 n/fission
Mean fission neutron spectrum energy	2.13–2.15 MeV
Prompt γ-ray multiplicity (mean)	~10/fission
Average prompt γ-ray energy	0.7–0.9 MeV

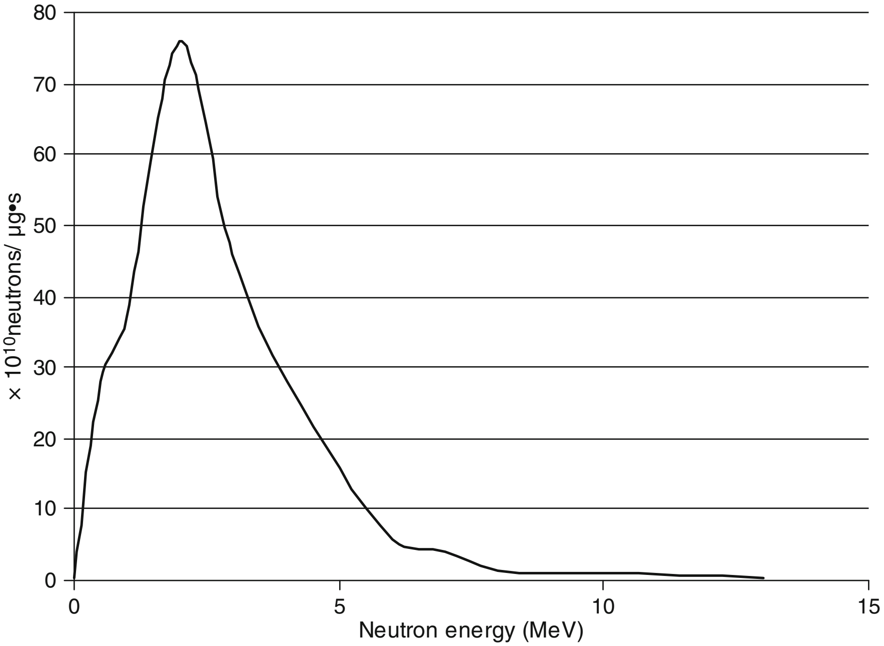

Fig. 5.1 Neutron energy spectrum from spontaneous fission of Cf-252 (total = 2.31×10^{12} neutrons/μg·s)

96.9 %, of Cf-252 decays are through alpha decay, but due to the nature of encapsulation, these He-4 nuclei do not escape the confines of the source. A small 3.092 % but significant proportion of Cf-252 decays via spontaneous fission which produces fission fragments, as well as a neutron yield of 3.768 n/fission (2.31434×10^{12} neutrons/s/g of Cf-252). The Cf-252 neutron energy spectrum is shown in Fig. 5.1. These neutrons have an energy spectrum which can be modelled as either a Maxwellian or a Watt fission spectrum. The National Bureau of Standards (NBS) evaluated this spectrum (Table 5.2) and made compensation for the deviations from an ideal Maxwellian spectrum with the use of energy-dependent adjustment functions. The relative uncertainty in the NBS neutron energy spectrum is small, with exceptions of the relative uncertainties in the 0–0.25 and 8–12 MeV groups. However, the number of neutrons emitted in these two energy groups is small,

Table 5.2 NBS evaluation of the Cf-252 neutron spectrum [5] $X_{\mathrm{Cf}}=[0.6672(E)^{1/2}\exp(-E/1.42)]\cdot\mu(E)$, where E is in MeV

Energy interval (MeV)	$\mu(E)$	Relative uncertainty (1σ) (%)
0–0.25	$1+1.20E-0.237$	±13
0.25–0.8	$1-0.14E+0.098$	±1.1
0.8–1.5	$1+0.24E-0.0332$	±1.8
1.5–6.0	$1-0.00062E+0.0037$	±(1.0–2.1)
6.0–20	$1.0\exp[-0.03(E-6.0)]$	±8.5

compared with the total neutron emission. Other Cf-252 emissions include prompt gammas and also photons from the fission products [2]. The total gamma emission spectrum is shown in Fig. 5.2.

5.2 Californium-252 Medical Sources

Clinical brachytherapy (interstitial and intracavitary) can be performed with essentially three different types of source designs: seed, needle, and applicator tube. Seed sources are more often used in the form of a flexible assembly. The characteristics of these Cf-252 medical sources are summarised in Table 5.3.

The clinical application of needls and flexible Cf-252 sources are limited because of their low neutron activity. On the other hand, the maximum possible licensed activity cannot be more than 100 µg of Cf-252 because of the neutron dose incurred by medical personnel during manual loading into patients. Use of miniature high activity more than 1 mg of Cf-252 (2.5×10^{9} n/s), remotely, afterloaded sources, significantly reduce treatment times, eliminate radiation hazard to the medical staff, and expedite treatment of brain and other tumours.

5.3 Dosimetric Properties of Cf-252 Sources

The dose deposition in tissue, in the vicinity of the Cf-252 source, is well known and basically has four components:

$D=D_{\mathrm{n}}+D_{\gamma}+D_{\mathrm{n}\,\gamma}+D_{\mathrm{p}}$ (primary neutron dose, primary photon dose, secondary photon dose, and proton dose).

The primary neutron dose is produced by the emitted neutrons with properties described above. This main component of the total absorbed dose in the tissue decreases rapidly with increasing distance from the source. The primary photon dose is due to the photons emitted by source, either from the spontaneous fission or by decay by-products. Close to the source, the photon dose is about half of the neutron component (see Fig. 5.3), but due to the increased penetrating ability through the tissue of photons compared to the neutrons, its proportional contribution increases at larger distances. The secondary photon dose is due to radiation capture of slow neutrons by hydrogen. Contribution of this component depends on the

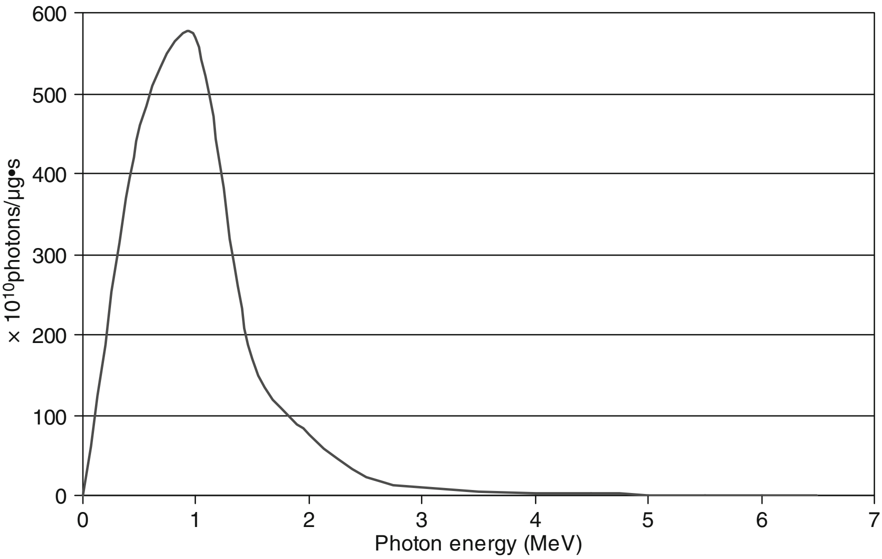

Fig. 5.2 Photons energy spectrum from spontaneous fission of Cf-252 (total = 1.322×10^{13} photons/μg·s)

Table 5.3 Properties of Cf-252 medical sources

Source type	Neutron fluence n/s	Source size (mm)		Encapsulation	Country of origin
		Diameter	Length		
Needle	2×10^6–1.5×10^7	1.2	15–35	1	Russia
	1.7×10^6–3.5×10^6	0.96	18–33	1	USA
	2.6×10^6–5×10^6	1.2	35	1	Germany
Flexible	5.5×10^6–1×10^7	1.1	40–60	1	Russia
	3.5×10^6–8×10^6	1.1	30–80	1	USA
	3.0×10^6–6×10^6	1.0	40–90	1	France
Applicator tube	2.3×10^7–3.7×10^9	3.0	15	2	Russia
	4.6×10^7–2.3×10^9	2.8	14–23	2	USA
	2.3×10^8	4.7	9.8	2	Japan

fluence of slow (thermalized) neutrons at the point of interest. It is negligibly small close to the source, but quite significant at distances up to 2–3 cm (see Fig. 5.4). The proton dose is a consequence of the $^{14}N(n,p)^{14}C$ capture reaction, and its contribution also depends on the thermal neutron fluence.

5.4 Clinical Applications of Cf-252 Sources

Needles and seeds of Cf-252 have been used clinically for interstitial soft tissue implants and surface applicators. These treatment techniques require manual loading of radioactive sources and are almost obsolete nowadays due to radiation

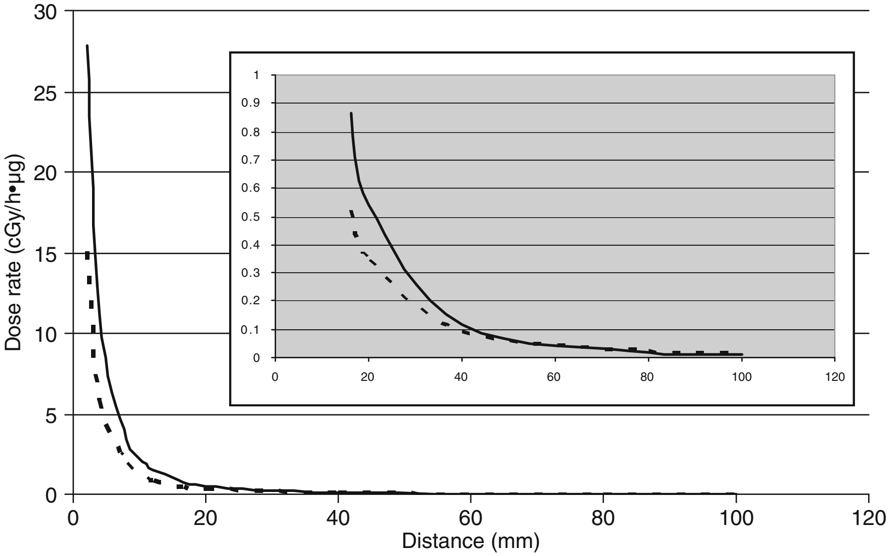

Fig. 5.3 Neutron and gamma absorbed dose rate (cGy/h·µg) in homogeneous tissue equivalent media from HDR afterloader source (active part diameter 1.5 mm, length 1 cm) [6]

protection concerns. Such sources are also of little interest to BNCT as the neutron fluence is far too low. The tube sources, on the other hand, with activities from more than 1 mg of Cf-252, produce considerably higher neutron fluences and may be of interest for BNCT.

Cf-252 remote afterloading devices with three sources (two “ovoids” and “tandem” with initial activities of 0.4 and 1.3 µg of californium, respectively) have been designed for gynaecological applications [7]. The physical size of the source also allows their application for the treatment of other cancer sites, such as rectum, esophageal, and brain tumours. Considering the sufficiently high fluence of thermal neutrons from this type of source and the increase in the relative fluence of slow neutrons with distance (see Fig. 5.4), some investigators have explored boron-10 enhancement Cf-252 brachytherapy [8]. Administration of a B-10 compound to the treatment site combined with the insertion of high activity Cf-252 into the tumour can improve significantly the dose distribution, especially in areas of micro-invasion. However, current boron drugs are still viewed as giving insufficient tumour-to-blood and tumour-to-tissue concentrations.

For the treatment of bulky brain tumours, it is essential that the dose distribution is conforming to the irregularly shaped, gross target volume and at the same time, delivers the necessary dose to the areas of clinically suspected disease. Due to the symmetrical nature of the dose distribution from a single Cf-252 source, these requirements are impossible to achieve in most cases. The use of small Gd-157 pellets (seeds or needles) as the NCT agent, in the case of bulky brain tumours, could provide the clinician with more flexibility to provide the desired dose distribution.

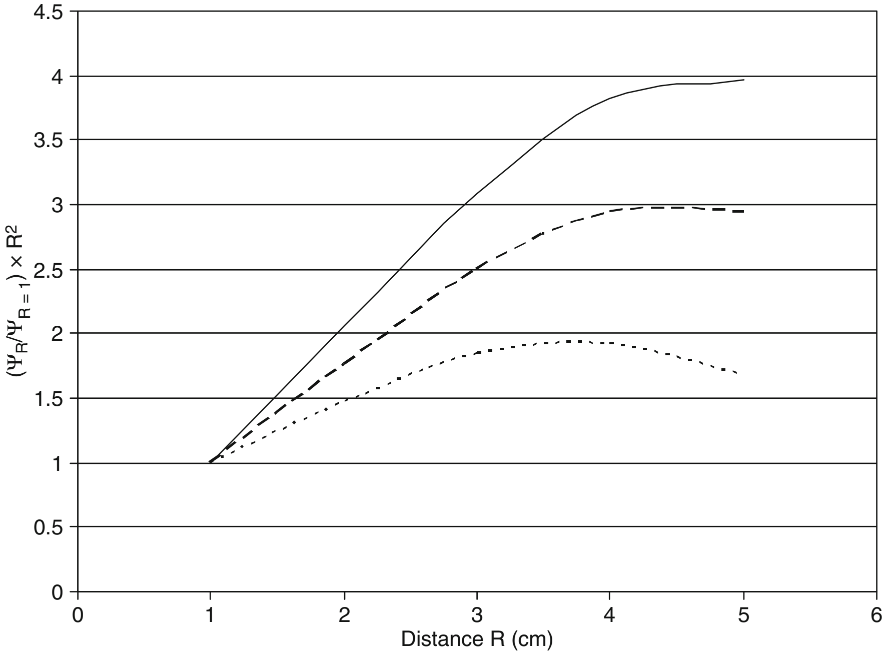

Fig. 5.4 The relative changes of thermal neutron fluence in tissue equivalent media. The fluence is normalised to 1 cm distance from the source and is corrected for inverse square law. *Solid line* – neutrons with energy $E = 1$ keV, *dashed line* – neutrons with energy $E = 10$ keV, *dotted line* – neutrons with energy $E = 100$ keV [7]

References

1. Fields PR et al (1956) Transplutonium elements in thermonuclear test debris. Phys Rev 102:180–182
2. Knauer JB, Alexander CW, Bigelow JE (1991) Cf-252 properties, production, source fabrication and procurement. Nucl Sci Appl 4:3–17
3. Browne E, Firestone RB, Shirley VS (eds) (1986) Table of radioactive isotopes. Wiley-Interscience, New York, pp 249–1 – 254–1
4. Axton NE (1987) Intercomparison of neutron source emission rates (1979–1984). Metrologia 23:129–144
5. Grundl J, Eisenhauer C (1975) Fission rate measurements for materials neutron dosimetry in reactor environments. In: Proceedings of the first ASTM-EURATOM symposium on reactor dosimetry, Petten, 1975, pp 425–454
6. Anderson LL (1986) Cf-252 physics and dosimetry. Nucl Sci Appl 2:273–282
7. Zyb A (ed) (1996) Effects of Cf-252 gamma-neutron irradiation. Energoatomizdat, Moscow
8. Maruyama Y (1984) Cf-252 neutron brachytherapy an advance for bulky localized cancer therapy. Nucl Sci Appl 1:677–748