

Chapter 1. THE HAZARD DEFINED

Neutron Production

In a medical electron accelerator installation, electrons and photons are the particles intentionally produced in order to destroy cancerous cells, thus producing the desired therapeutic effect. When these particles impinge on surrounding materials assembled in the treatment head, the electrons may undergo electro-neutron ($e,e'n$) interactions and the photons may undergo photoneutron (γ,n) interactions. The former is about 100 times less probable than the latter. Both types of interaction produce neutrons that are not intended but come as a by-product. Shielding is necessary so that the patient, the staff and the public are not exposed to any accidental 'neutron therapy'.

Sources of neutron contamination in the treatment head include walls of vacuum chamber, walls of waveguide, x-ray target, beam extractor, filters, collimators, transmission ionisation chambers and light localizers. A treatment head is shown in Figure 1-1.

Apart from the treatment head, other sources of photoneutrons include the patient, the air and the walls of the bunker. The problem is further aggravated if high density materials, usually metal, are embedded in the walls - intended for shielding photons but at the same time act as sources of photoneutrons as well. The neutron dose equivalent outside the bunker would be higher if the barriers contain lead or steel compared to the case where pure concrete barriers are used. The recent excitement of conformal therapy brings in the multileaf collimator, usually made of lead, which can be another source of photoneutrons as well. A treatment head with multileaf collimator installed is shown in Figure 1-2.

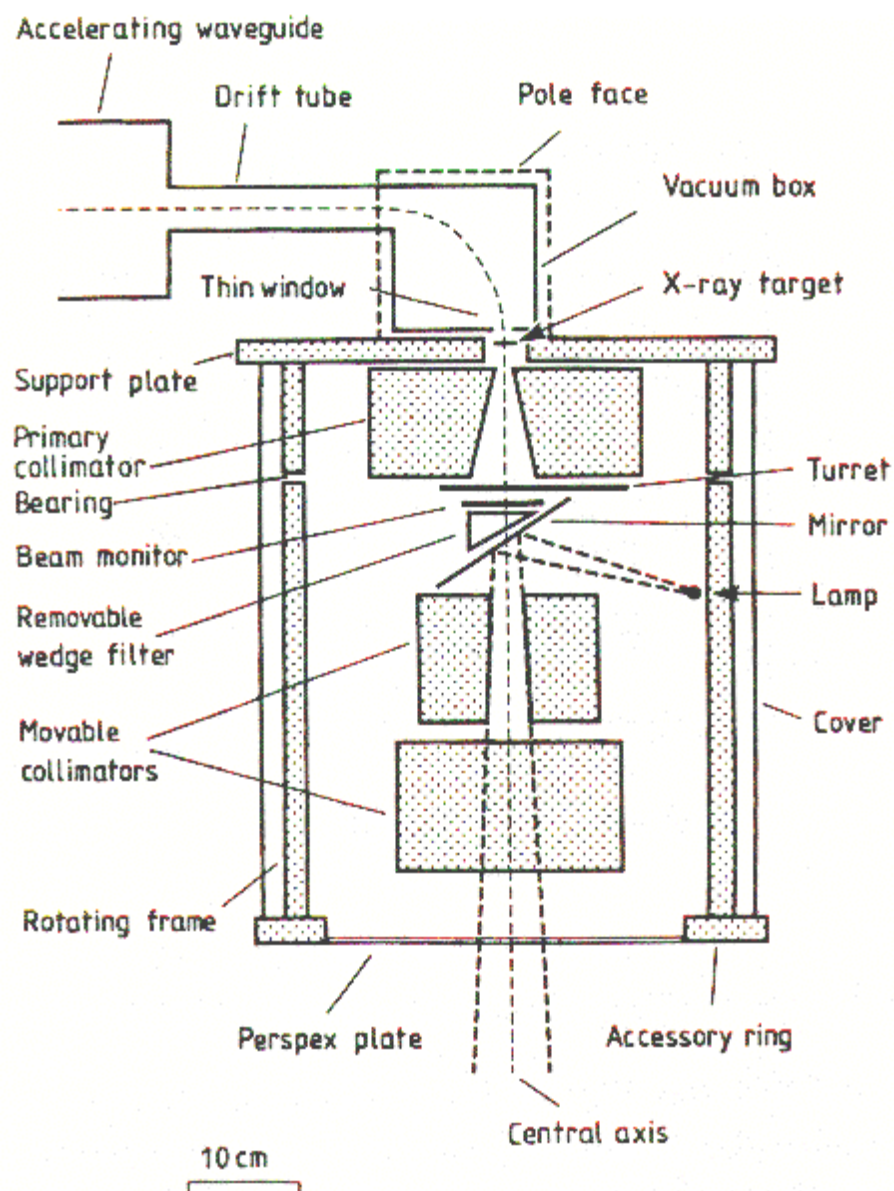


Figure 1-1. The treatment head of a medical linear accelerator. [GRE 85]

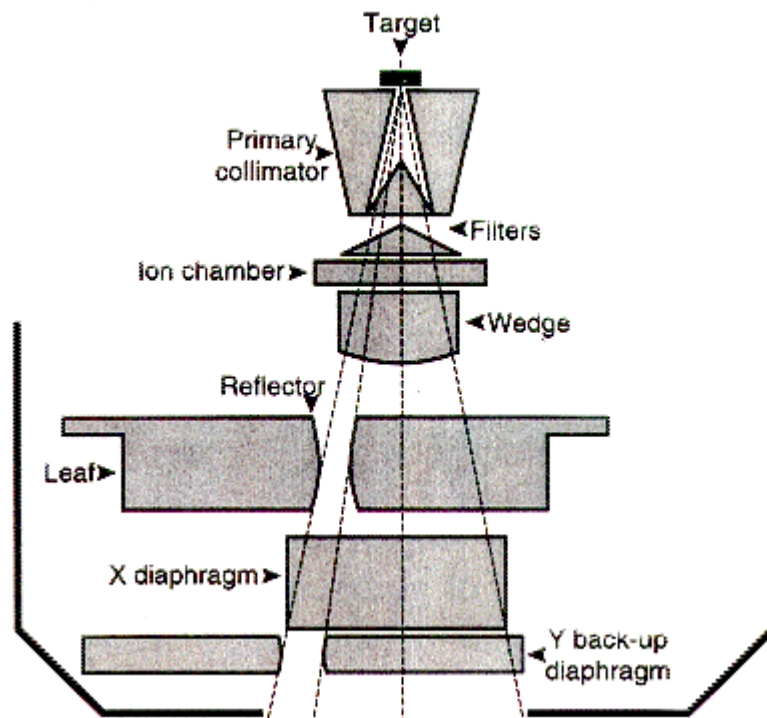


Figure 1-2. A treatment head with multileaf collimator installed. [GRE 85]

Photoneutron production is governed by the neutron separation energy and the photoneutron cross-section. The neutron separation energy is the threshold energy that must be overcome in order for the interaction to occur. The neutron separation energies for a range of isotopes are calculated and tabulated in Table 1-1. It shows that even at photon energies below 10 MeV, lead and tungsten are capable of producing neutrons. At the photon energies between 10 and 20 MeV, more other materials are likely to undergo the (γ, n) interaction while lead and tungsten are even capable of producing neutron pairs, as shown in Table 1-2.

Isotopes of interest include ^1H , ^{16}O , ^{12}C and ^{14}N in the patient's body, ^{16}O and ^{14}N in the air, ^{184}W , ^{208}Pb and ^{27}Al in the treatment head and treatment accessories, also ^1H , ^{16}O , ^{28}Si , ^{40}Ca and ^{12}C in the concrete walls. ^{10}B and ^{11}B are sometimes used for maze lining to shield against neutrons.

Once the interaction threshold is overcome, neutrons emerge with kinetic energies which can be calculated as well. This is tabulated in Table 1-3.

Table 1-1. Photo-neutron production by (γ, n) interaction.

ELEMENT	Z	A Of TARGET NUCLIDE	(γ, n) THRESHOLD (MeV)	A of PRODUCT NUCLIDE	Half-life
O	8	16	15.7	15	122 s
C	6	12	18.7	11	20.4 m
N	7	14	10.6	13	9.96 m
Al	13	27	13.1	26	.72 My
W	74	182	8.1	181	121 d
		183	6.2	182	Stable
		184	7.4	183	Stable
		186	5.8	184	Stable
Pb	82	206	8.1	205	15 My
		207	6.7	206	Stable
		208	7.4	207	5.8 h
Si	14	28	17.2	27	4.13 s
Ca	20	40	15.6	39	.86 s
Mg	12	24	16.5	23	11.3 s
Fe	26	54	13.4	53	Stable
		56	11.2	55	2.7 y
Na	11	23	12.4	22	2.60 y
K	19	39	13.1	38	7.61 m
B	5	10	8.4	9	Stable
B	5	11	7.2	10	Stable

Table 1-2. Photo-neutron production by ($\gamma, 2n$) interaction.

ELEMENT	Z	A of TARGET NUCLIDE	($\gamma, 2n$) THRESHOLD (MeV)	A of PRODUCT NUCLIDE	Half-life
O	8	16	28.89	14	71 s
C	6	12	31.84	10	19 s
N	7	14	30.62	12	11 ms
Al	13	27	24.42	25	7.18 s
W	74	184	13.60	182	Stable
Pb	82	208	15.30	206	Stable
Si	14	28	30.49	26	2.21 s
Mg	12	24	29.68	22	2.86
Fe	26	56	20.50	54	Stable

Table 1-3. Kinetic energies of emerging neutrons.

ELEMENT	INCIDENT PHOTON ENERGY (MeV)			
	10	15	20	25
	Kinetic Energy of Neutrons (MeV)			
O	-	-	4.3	9.3
C	-	-	1.3	6.3
N	-	4.4	9.4	14.4
Al	-	1.9	6.9	11.9
W	2.6	7.6	12.6	17.6
Pb	2.6	7.6	12.6	17.6
Si	-	-	2.8	7.8
Ca	-	-	4.4	9.4
Mg	-	-	3.5	8.5
Fe	-	3.8	8.8	13.8
Na	-	2.6	7.6	12.6
K	-	1.9	6.9	11.9
B	1.6	6.6	11.6	16.6
B	17.2	22.2	27.2	32.2

When a photoneutron interaction takes place, one or more neutrons may be produced. Therefore the photoneutron production cross-section is the sum of $\sigma(\gamma,1n)$, $\sigma(\gamma,2n)$, $\sigma(\gamma,3n)$ and so on, where $\sigma(\gamma,1n)$ usually contributes most. The photoneutron yield cross-section, on the other hand, is the sum of $\sigma(\gamma,1n)$, $2\sigma(\gamma,2n)$, $3\sigma(\gamma,3n)$, etc. When a single neutron is produced, it may be accompanied by alphas or protons. The same is true for $\sigma(\gamma,2n)$, $\sigma(\gamma,3n)$, etc. Therefore, $\sigma(\gamma,1n)$ itself is a sum of $\sigma(\gamma,n)$, $\sigma(\gamma,n\alpha)$ and $\sigma(\gamma,np)$.

The (γ,xn) and (γ,n) cross sections for ^{12}C and ^{16}O , copper and ^{208}Pb are given in Figures 1-3 and 1-4.

The photon absorption cross-section is different for each isotope and is a function of photon energy. The relation takes the form of a bell shape, where there is a giant resonance at which the photon absorption cross-section is maximum. If the giant resonance is broad and if the incident photon energy is located near the resonance, many particles will be emitted.

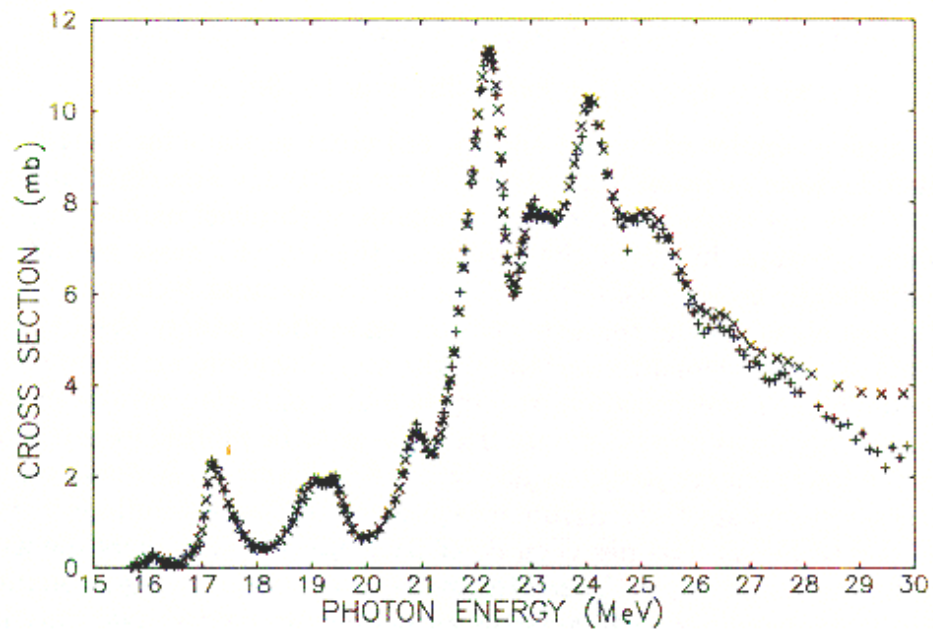
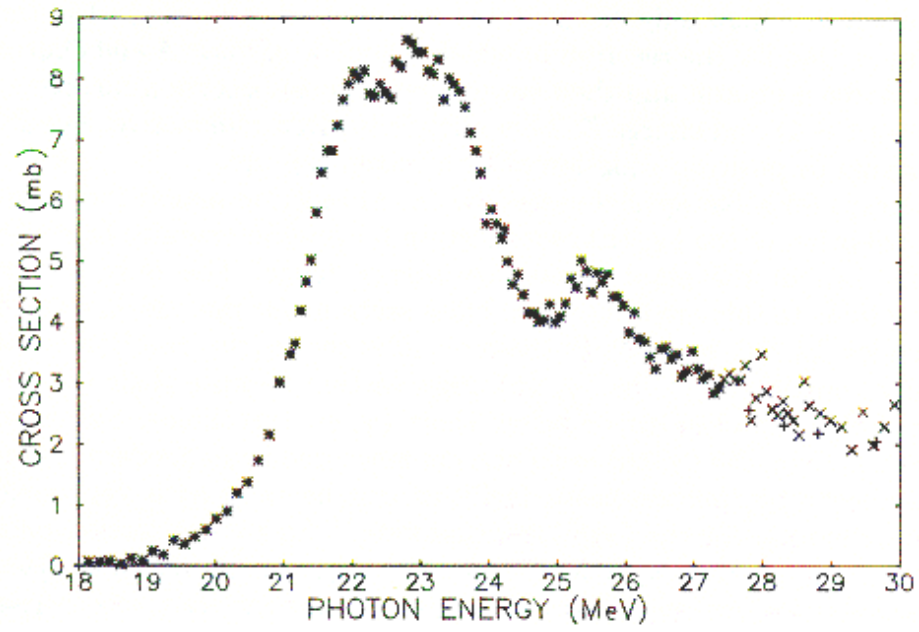


Figure 1-3. The (γ, xn) , represented as 'x', and (γ, n) , represented as '+', cross sections for ^{12}C (top) and ^{16}O (bottom). [NCR 84]

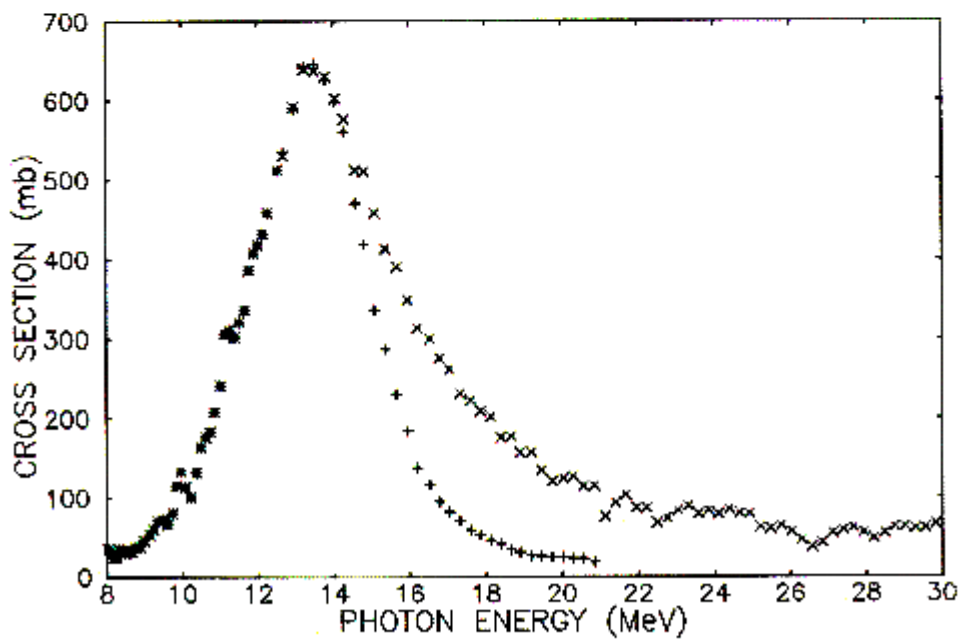
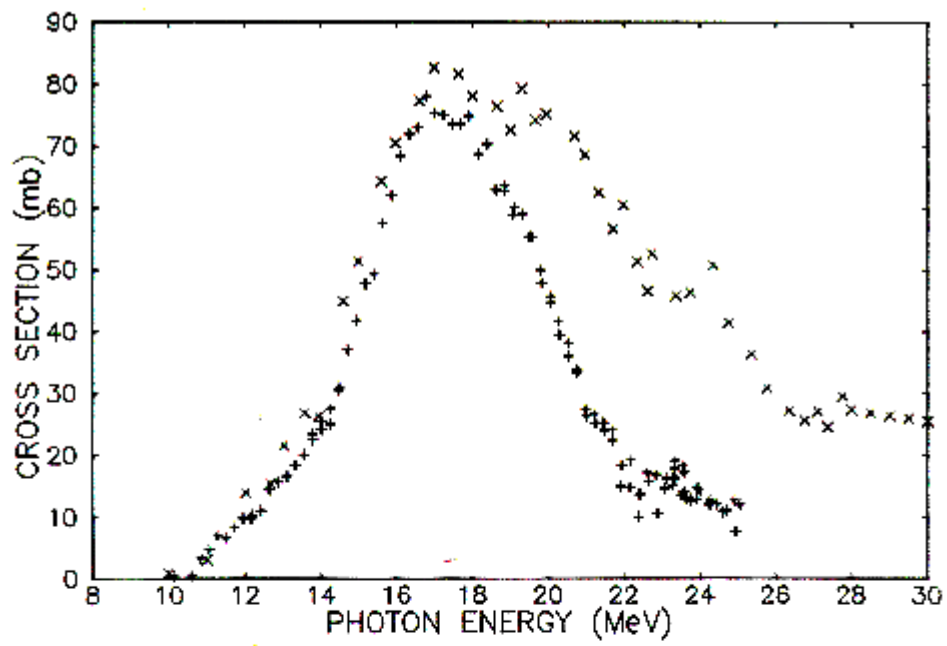


Figure 1-4. The (γ, xn) , represented as 'x', and (γ, n) , represented as '+', cross sections for copper (top) and ^{208}Pb (bottom). [NCR84]

Since the photons which initiate the photoneutron interactions come from the bremsstrahlung process, the ultimate neutron yield depends not only on the shape of the cross-section resonance curve, but also the shape of the bremsstrahlung spectrum generated by the electrons.

Figure 1-5 shows the neutron yield for different materials up to 40 MeV. A few materials requiring emphasis are those that form the target, which is usually an alloy. For instance, the Philips SL 75/5 linac has a 3mm-thick target composed of 95% tungsten, 3.75% nickel and 1.25% iron [LEW 99]. Figure 1-6 shows the relative neutron yield at different energies for a range of target thicknesses. Figure 1-7 and 1-8 show the photoneutron spectra from lead, carbon and oxygen.

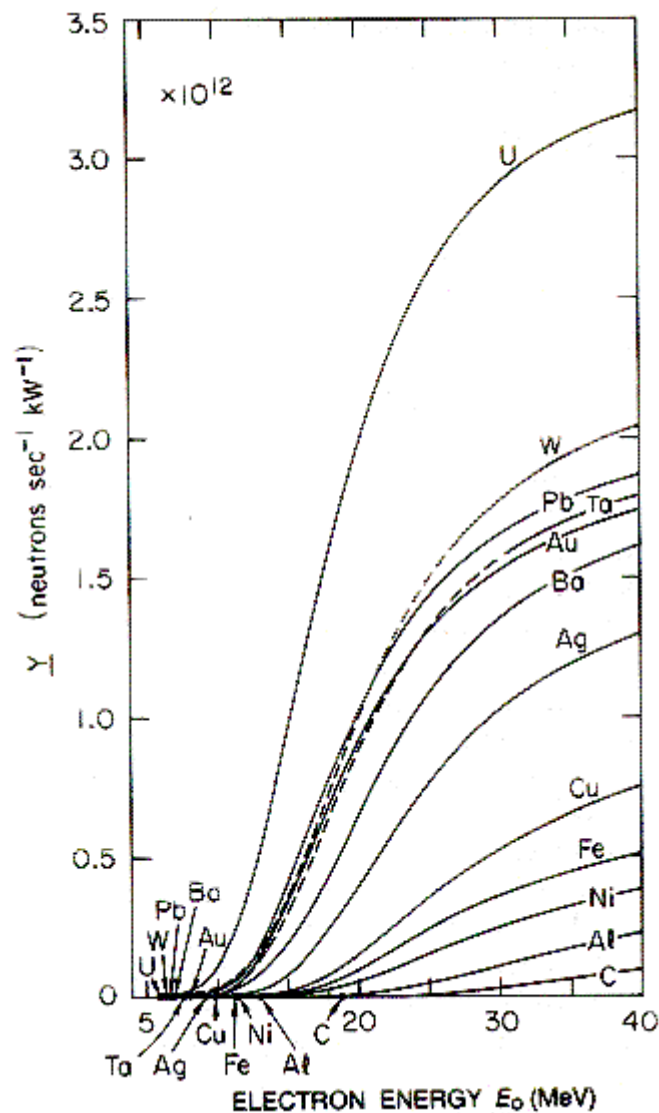


Figure 1-5. Thick target neutron yields. [SWA 79]

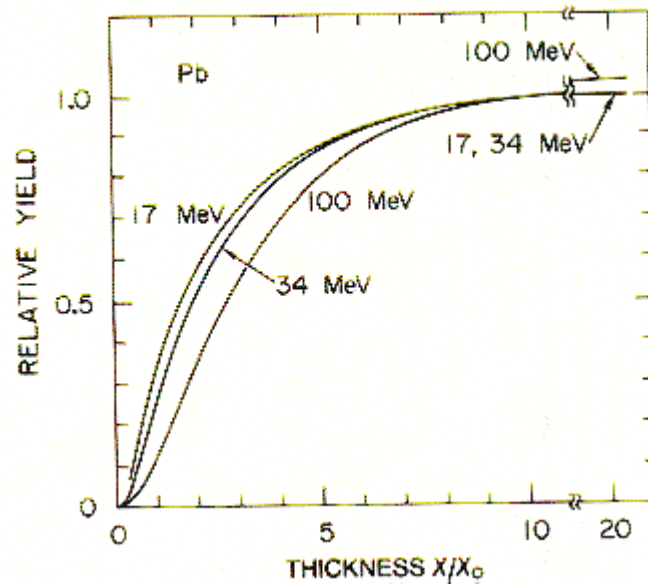


Figure 1-6. Relative neutron yield as a function of target thickness in radiation lengths X_0 . [SWA 78]

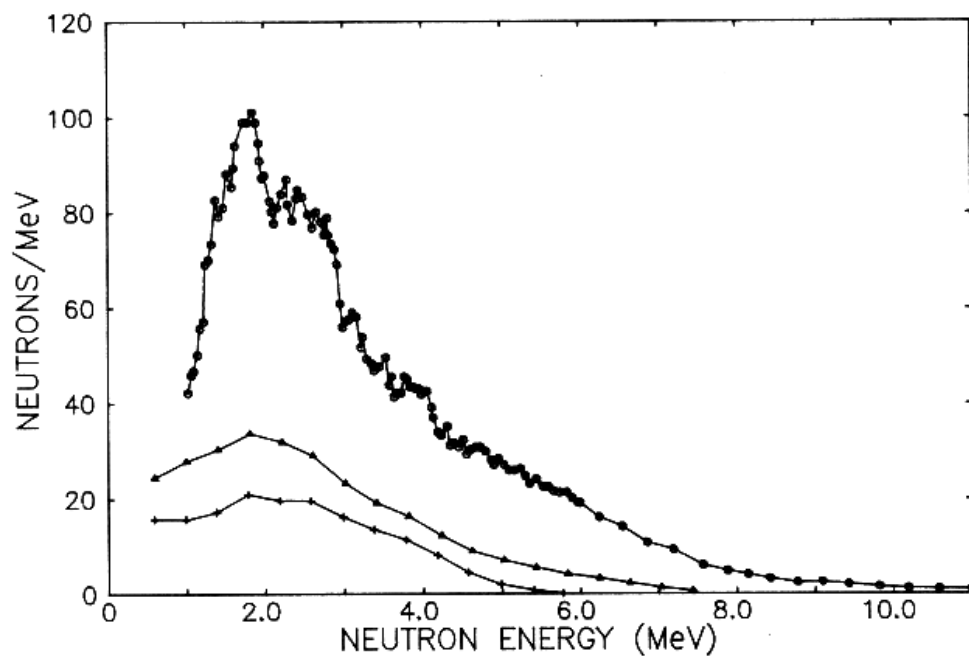


Figure 1-7. Photoneutron spectra from lead. Each of the 3 curves, starting from the top, is for 31, 15 and 13 MeV respectively. [NCR 84]

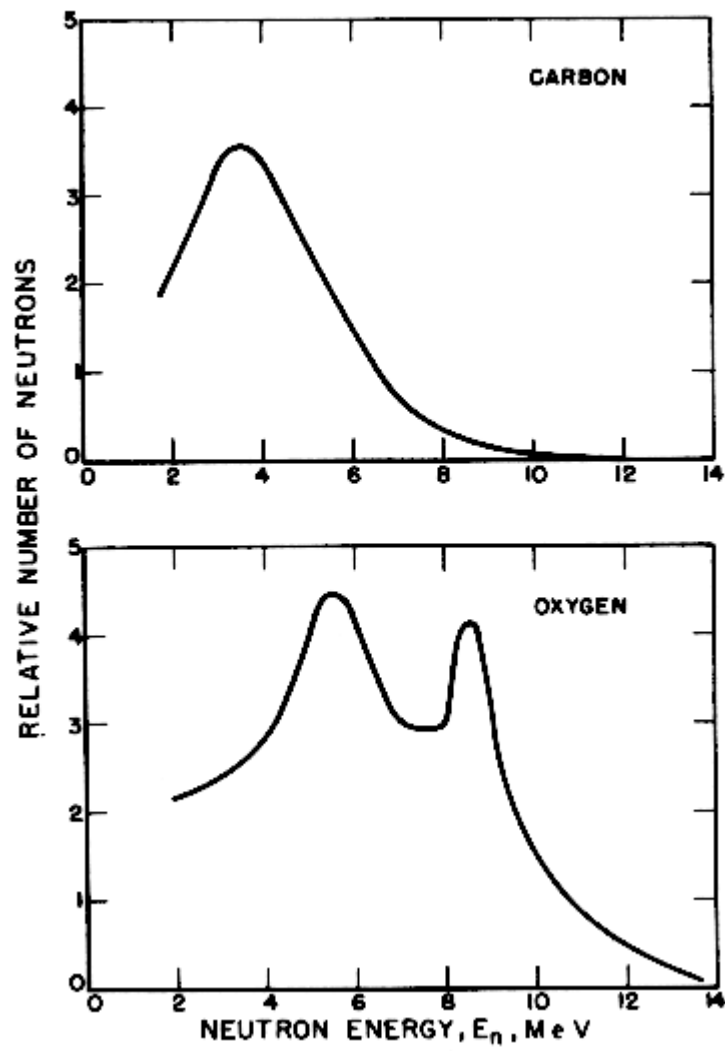


Figure 1-8 Photoneutron spectra from carbon and oxygen. [NBS 64]

Neutron Interactions

When neutrons or any neutron-induced radiation (eg. secondary photons) interact with tissues, energy is imparted to the tissues, causing biological hazard. The absorbed dose is the energy per unit mass imparted to the material by ionizing radiation. Depending upon the composition of the tissue, the interactions that occur between neutrons and tissue differ.

At epithermal energies, neutrons are moderated, i.e. slowed down, mainly by elastic scattering in hydrogen. Elastic scattering by hydrogen contributes up to 95% of the energy transferred by fast neutrons to tissue [NBS 64]. The elastic scattering process will be demonstrated using a C program in Chapter 3.

At higher energies, on the other hand, the predominant moderating effect comes from inelastic scattering in materials of high atomic number. This interaction does not occur at energies below the lowest excited state of the material. The lowest excited states for some isotopes are given in Table 1-4. It is difficult to quantify the energy loss due to inelastic scattering. More often than not, there will be a cascade of photon emissions and the relative yields need to be taken into account. It is only the minimum energy loss, which is equal to the energy of the lowest excited state, which can be readily quantified.

Table 1-4. First excited states.

ELEMENT	ATOMIC NUMBER	ABUNDANCE (%)	1 ST EXCITED STATE (MeV)
Pb	206	25.1	0.803
	207	21.7	0.570
	208	52.3	2.61
Fe	54	5.8	1.41
	56	91.7	0.847
W	182	26.4	0.100
	183	14.4	0.047
	184	30.6	0.111
	186	28.4	0.123

A third moderating process is the production of neutron pairs, i.e. the (n,2n) interaction which competes with inelastic scattering. Since the emerging neutrons have to share out the energy of the original neutron, each will have an energy lower than that of the parent neutron.

The capture process acts as a neutron sink, resulting in a decreasing number of neutrons. There are two types of capture: radiative capture and prompt disintegration. The important capture interactions in tissue are $^1\text{H}(n,\gamma)^2\text{D}$, which gives off a 2.2 MeV γ quantum, and $^{14}\text{N}(n,p)^{14}\text{C}$, which gives off a 600 keV proton.

Different interactions occur with different probabilities, which are energy and/or angle dependent. The probability of any interaction when a neutron passes through matter -- whether it is captured, elastically or inelastically captured -- is given by the corresponding neutron interaction cross-sections (expressed in barns).

Residual Activities

The unintended production of neutrons in the radiotherapy room leads to residual radioactivities. Both neutron emission and neutron capture are sources of residual radioactivities.

Neutron emission tends to yield isotopes that are neutron deficient and therefore unstable. Such isotopes may decay by giving off positrons, which in turn give off two 511 keV photons each. The degree of hazard depends not only on the abundance of the parent nuclide, but also on the half-life and the mode of decay of the daughter nuclide. In the event that the parent nuclide is low in abundance, the hazard is understandably lower.

The hazard is minimal if the half-life is extremely short (in which case the radioactivity dies off quick enough) or extremely long (in which case the decay rate is too slow to cause any harm). Neutron emission from aluminium, for instance, yields two isomeric forms, one of 6.7 seconds half-life and the other of 0.80 million years. As for the mode of decay, electron capture is not as much a cause for worry as positron emission.

Neutron capture requires separate discussions for fast neutrons and thermal neutrons. Capture of fast neutrons may result in particulate emissions, a special case being the multiplication of neutrons. Residual activity from capture of fast neutrons is generally insignificant, the worst case being the (n,α) reaction on

aluminium, producing ^{24}Na . For 1 g/cm^3 of aluminium, a 10^{13} per second fast-neutron flux would result in a saturation activity of 4mCi of ^{24}Na and a dose rate of 6 mSv/hr at one meter [NBS 64].

Capture of thermal neutrons takes place mainly in the concrete wall. The presence of sodium and manganese can be serious. If the concrete contains 1.6% of sodium by weight, 4.8% of neutron capture will then be in sodium, producing ^{24}Na which has a half-life of 15 hours [NBS 64]. Manganese, on the other hand, has a capture cross-section of 13 barns and produces ^{56}Mn , which has a half-life of 2.6 hours and decays by gamma emission of up to 3 MeV.