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I. PHYSICS

Radiation Dosimetry

FAST NEUTRON DOSE TO BODY VIA TRACE ELEMENTS

K. K. MANOCHA

Department of Radiology, Medical College, Rohtak (Haryana)

and

R. K. MOHINDRA

Department of Physics, Kurukshetra University, Kurukshetra (Haryana)

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The present paper summarises the results of already computed fast neutron doses to the body via various constituent elements of the body. The maximum permissible dose of fast neutrons has been discussed. The applications of the calculations are listed.

Keywords: Dose, elastic and inelastic; Reactions; Trace elements; Transmutations.

INTRODUCTION

THE rationale for using fast neutrons for the treatment of cancerous tumours lies in their low oxygen enhancement ratio (O.E.R.) and high linear energy transfer (L.E.T.). A fast neutron while interacting with the nuclei of the atoms of cellular molecules will generate high L.E.T. ionising radiations—α, p, d, etc., and recoiling residual, nuclei (Csikai *et al.*, 1963) which will change the molecules by direct or indirect action. At the same time, the parent cellular molecules (with whose atoms neutron has interacted) will also be changed through the nuclear reactions i.e., parent and residual nuclei are different. The changes produced because of the nuclear transmutations will be permanent ones and, hence less chances of recovery of cells. Thus for studying toxic effects of fast neutrons on human body, not only an accurate analysis of nuclear reactions with major body elements (H, C, N and O) but also with trace elements Ca, P, S, K, Na, Cl, Mg and Fe etc., assumes considerable importance. This type of 14 Mev neutron dosimetry calculations will be of great help for fast neutron therapy and radiation protection of fast neutron workers.

METHOD OF DOSE CALCULATIONS

For studying quantitatively the effects of ionising charged particles released in fast neutron reactions with body cell elements, their energy spectra and cross-sections of the corresponding nuclear reactiors are required. The analysis of energy spectra and evaluation of cross-sections have been made using better (Manocha & Mohidra, 1973; and Wadhwa *et al.*, 1974) level density equations of Newton (1956). The detailed method of dose calculations has been given earlier (Manocha & Mohindra, 1977, 1978, 1979*a*, *b*). The total amounts of body constituent elements have been taken from Spiers (1968) and are given in Table I.

TABLE I

*Average chemical composition of the adult human body**

S.No.	Element	Percent by weight	Amount in a 70 kg man in grams	No. of atoms per gram of 70 kg man
1.	Oxygen	65.0	45500	2.4468 $\times 10^{22}$
2.	Carbon	18.0	12600	2.9034 $\times 10^{22}$
3.	Hydrogen	10.0	7000	6.0230 $\times 10^{22}$
4.	Nitrogen	3.0	2100	0.129 $\times 10^{22}$
5.	Calcium	1.5	1050	0.0226 $\times 10^{22}$
6.	Phosphorus	1.0	700	0.0194 $\times 10^{22}$
7.	Sulphur	0.25	175	0.0047 $\times 10^{22}$
8.	Potassium	0.20	140	0.0031 $\times 10^{22}$
9.	Sodium	0.15	105	0.0039 $\times 10^{22}$
10.	Chlorine	0.15	105	0.0026 $\times 10^{22}$
11.	Magnesium	0.05	35	0.0013 $\times 10^{22}$
12.	Iron	0.0057	4	0.000061 $\times 10^{22}$

*Spiers (1968).

DISCUSSION OF RESULTS

Dose to the Body via Trace Elements

The detailed evaluated doses via various nuclear reactions of neutrons around ^{14}MeV with ^{56}Fe, ^{40}Ca, ^{31}P, ^{39}K, ^{35}Cl and ^{32}S have been given earlier (Manocha & Mohindra, 1977, 1978, 1979*a*, *b*). The approximate dose rates to the body via ^{23}Na and ^{24}Mg are given in Tables II and III. Since compound nucleus theory cannot give good results of cross-sections for these light nuclei, the experimental values (Cullen *et al.*, 1976, 1977) of cross-sections have been used for calculating the dose. The approximate average energies of the emitted particles have been estimated from shape of spectra.

TABLE II

Dose to body via sodium

S. No.	Nuclear Reaction	Q value in MeV	Experimental σ (mbs) near 14 MeV	(Emitted particle + Recoil nucleus) Energy MeV	Computed dose to body in rad per unit neutron flux
1.	^{23}Na(n, n) ^{23}Na elastic	0	280	1.13 (recoil)	19.7 $\times 10^{-14}$
2.	^{23}Na(n, n') ^{23}Na inelastic	0	650	2.5 + 0.65	26.4 $\times 10^{-14}$
3.	^{23}Na(n, $2n$) ^{22}Na	-12.4	28 ± 2	1.0 + 1.10	1.9 $\times 10^{-14}$
4.	^{23}Na(n, p) ^{23}Ne	-3.6	43 ± 8	4.5 + 0.88	14.4 $\times 10^{-14}$
5.	^{23}Na(n, α) ^{20}F	-3.87	150 ± 20	5.5 + 0.93	60.2 $\times 10^{-14}$
6.	^{23}Na(n, $n\alpha$) ^{19}F	-10.5	20	2.5 + 1.10	4.5 $\times 10^{-14}$
				Total	1.27 $\times 10^{-12}$

TABLE III

Dose to body via magnesium

S. No.	Nuclear Reaction	Q value in MeV	Experimental σ (mbs) near 14 MeV	(Emitted particle + Recoil nucleus) Energy MeV	Computed dose to body in rad per unit neutron flux
1.	^{nat}Mg(*n*, *n*) elastic	0	820 ± 100	1.08 recoil	18.4×10^{-14}
2.	^{nat}Mg(*n*, *n'*) Mg inelastic	0	640	2.5 + .72	9.6×10^{-14}
3.	^{24}Mg(*n*, *p*) Na^{24}	−4.73	200 ± 20	5 + .91	24.6×10^{-14}
4.	^{nat}Mg(*n*, 2*n*) 78.6% ^{24}Mg	−16.5			
	10.1% ^{25}Mg	−7.3	60	2 + .89	0.1×10^{-14}
	11.3% ^{26}Mg	−11.1			
				Total	0.53×10^{-12}

The total first collision neutron (arouud 14 MeV) doses per unit neuron flux to a standard man via various trace elements are about

Calcium—1.86×10^{-11} rad	Phosphorus—1.30×10^{-11} rad
Potassium—2.85×10^{-12} rad	Sulphur—2.78×10^{-12} rad
Chlorine—2.01×10^{-12} rad;	Sodium—1.27×10^{-12} rad
Magnesium—0.53×10^{-12} rad;	Iron—1.65×10^{-11} m rad

Dose to Standard Man via various Nuclear Processes

The dose to body and various tissues via major body elements H, C, N and O for around 14 MeV neutron energy has been evaluated (Manocha & Mohindra 1979*a*, *b*) The total dose contributed by elastically scattered protons (due to hydrogen present in the body) is about 65.9 per cent and by C, N, O and trace elements about 34.1 per cent (Table IVa). Out of this (34.1 per cent) about 6.6 per cent is by elastic process, about 5.2 per cent is by inelastic process and about 22.3 per cent is by nuclear reactions (from the data in Table IVb). Further analysis of dose via nuclear reactions shows, about 90 per cent is contributed by alpha particles and recoils of heavy nuclei and rest of the dose is contributed by protons. The elastic and inelastic contributions are only through the recoils of the heavy nuclei. The quality factors for protons-10; for alpha particles-20; for recoiling nuclei-20, have been given by NCRP (1971) and quoted by Cameron and Skofronick (1978). With these quality factors, the dose equivalent contributed by C, N, O and trace elements is about the same as dose equivalent contributed by hydrogen recoils alone. The details are given in Table V. This confirms the assumption made by Bewley (1968) (and stated earlier — Manocha & Mohindra, 1979*a*, *b*) to reconcile his results of theoretically calculated O.E.R. with experimental value of O.E.R.

Maximum Permissible Dose of Neutrons

The maximum permissible exposure of fast neutrons (10–30 MeV) for a 40hr working week has been listed (Marion & Young, 1968) as $10 n/cm^2$ sec. The total

TABLE IV(a)

No. of atoms per gm in standard man-n	$d = \Sigma\sigma \times E$ MeV-barn
H -6.023×10^{22}	5.052
C -0.9034×10^{22}	3.465
N -0.1291×10^{22}	5.033
O -2.4468×10^{22}	4.781
Other elements, $\Sigma d \times n =$	0.24×10^{22} MeV-barn/gm

TABLE IV(b)

Nuclear process	d for nuclear process (via)			
	H	C	N	O
Elastic	5.052	0.71	0.47	0.94
Inelastic	—	0.69	0.52	0.69
Nuclear Reactions	—	2.07	4.04	3.15

Further analysis of dose via nuclear reactions shows that (n, α) reactions and heavy recoils contribute *about* 90% of the dose by nuclear reactions while protons contribute *about* 10%

TABLE V

Total dose absorbed by the body/(unit neutron flux-ϕ)	$= 7.38 \times 10^{-9}$ rad
The dose equivalent/ϕ contributed by n-p scattering (65.9%)	$= 4.86 \times 10^{-9}$ rad
	$= 48.6 \times 10^{-9}$ rem
The dose contributed/ϕ by C, N, O and trace elements (34.1%)	$= 2.52 \times 10^{-9}$ rad

Out of this (34.1%) dose, 90% is contributed by alpha particles and heavy recoils and 10% by protons.

Therefore, dose equivalent contributed by alphas and heavy recoils & protons	$= 2.268 \times 10^{-9} \times 20 + 0.252 \times 10^{-9} \times 10$ rem/ϕ
	$= 47.68 \times 10^{-9}$ rem/ϕ

Hence dose equivalent (rem) contributed by n-p scattering $\simeq$ dose equivalent (rem) contributed by alphas and heavy recoils and protons (per unit flux).

TABLE VI

Total dose absorbed by the body per unit neutron flux	$= 7.38 \times 10^{-9}$ rad
Total dose absorbed by the body per unit neutron flux for 1 year	$= 3600 \times 52 \times 40 \times 7.38 \times 10^{-9}$ rad/yr
(for a 40 hour/week)	$= 55.3 \times 10^{-3}$ rad/yr
Safety limit for neutrons is 10 n'/cm^2-sec for a flux of 10 neutrons/cm^2. sec, total absorbed dose	$= 0.553 \simeq 0.55$ rad/yr
The dose equivalent contributed by n-p scattering (65.9%)	= 0.364 rad or 3.64 rem/yr
The dose contributed by C, N, O and trace elements (34.1%)	= 0.189 rad per yr

Out of this dose (0.189 rad) 90% is via alpha particles, heavy recoils and 10% is via protons.

The dose equivalent contributed by C, N, O and trace elements	$= (0.170 \times 20 + 0.0189 \times 10)$ rem/yr
	= 3.59 rem/yr
Total dose equivalent to the body $\simeq$ 7.2 rem/yr	

absorbed dose (details given in Table VI), on the present calculations comes out to be about 0.55 rad per year. Using the quality factors as mentioned earlier in the present work, the dose equivalent comes out to be about 7.2 rem per year which is higher than the recommended (Cameron & Skofronick, 1978) maximum permissible dose equivalent of 5 rem per year.

Application of the Calculations

(*i*) The computed $\sigma^{n'}$ cross-sections and the average energies of the emitted particles may prove useful for evaluating neutron hazards in the vicinity of neutron generators and thus become helpful in the design of shielding of neutron sources.

(*ii*) The computed cross-sections will be useful for evaluating the amounts of elements, *in vivo*, in animals (Anderson *et al.*, 1964, Cohn & Dombrowski, 1971, Palmer, 1973). The computed doses (neutron and induced activity) will be useful for estimating the radiation hazards involved in these total body neutron activation analysis experiments.

(*iii*) The dose to bone via calcium and phosphorus will be useful for relating neutron flux exposure to dose (Manocha & Mohindra, 1978) in bone tumor radiotherapy.

(*iv*) The inducd activity doses will give an idea of radiation hazards involved in neutron therapy.

Nuclear reactions will definitely, to some extent, result in nuclear transmutations of the body elements. These resulting new nuclei will have rearrangement of orbital electrons resulting in changed biochemistry of the body. Also the functions performed by original atoms of the molecules in the cells may be impaired. Some of the trace elements present in the cells may be performing vital functions for the cell or body. These changes produced may have toxic effects in the cells because of nuclear transmutations and may be permanent ones with few chances of recovery. It has been confirmed experimentally (Andrews, 1968; and Rafla & Rotman, 1974) that there is reduced cell recovery from partial damage due to neutrons Our detailed calculations are the first physical quantitative analysis in this direction.

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