# FAST NEUTRON DOSE CONTRIBUTION FOR $^{39}K$, $^{35}Cl$ AND $^{32}S$

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Using the compound nucleus model theory, an attempt has been made to analyse nuclear reactions like $(n, n)$, $(n, 2n)$, $(n, np)$, $(n, n\alpha)$, $(n, p)$, $(n, pn)$, $(n, pp)$, $(n, p\alpha)$, $(n, \alpha)$, $(n, \alpha n)$, $(n, \alpha p)$ and $(n, \alpha\alpha)$ induced by 14.1 MeV neutrons with $^{39}K$, $^{35}Cl$ and $^{32}S$. The computed spectra of the emitted particles have been used to evaluate the doses to the body *via* the above various nuclear reactions. The computed doses, cross-sections and energies of the emitted particles in the various nuclear reaction alongwith their recoil contributions are tabulated. The small beta and gamma dose rates to the body due to the induced activity of the residual nuclei $^{39}K(n, nn)\,^{38}K^*$, $^{35}Cl(n, p)\,^{35}S^*$, $^{35}Cl(n, \alpha)\,^{32}P^*$ $^{32}S(n, p)\,^{32}P^*$ and $^{32}S(n, pp)\,^{31}Si^*$ have been estimated and listed.

## INTRODUCTION

LOWER oxygen enhancement ratio (OER), reduced cell recovery from partial damage and lower differential absorption of the neutron beam in bone as compared to soft tissues, make neutrons more useful for radiotherapy than X and gamma rays (Smeer *et al.*, 1974). Theoretical values of OER have been calculated by Bewley (1968) and are greater than the measured values. To reconcile the calculated and measured values of OER at 14.6 MeV it would be necessary that 50 per cent of the dose should be received *via* alpha particles and heavy recoils instead of 30 per cent as calculated by Randolph (1957). Using some recent values of cross-sections, the dose to various tissues *via* H, C, N, O at 14.1 MeV has been recalculated (Manocha & Mohindra, *communicated*) and it is found that the dose received *via* alpha particles and heavy recoils is of the same order as calculated by Randolph (1957). Thus for the study of effect of neutrons on human body not only an accurate analysis of nuclear reactions with major body elements (H, C, N and O) but also with minor elements like Ca, P, S, K, Na, Cl, Mg and Fe etc., is required. The dose to the body *via* Fe and Ca & P has already been calculated (Manocha & Mohindra, 1977, 1978).

In the present work, an attempt has been made to evaluate dose to the body at 14.1 MeV neutrons *via* $^{39}K$, $^{35}Cl$ and $^{32}S$ through all possible nuclear reactions. The computed cross-sections presently used for dose calculations, may find in use activation analysis for evaluating the amounts of potassium, chlorine and sulphur in animals (McNeil *et al.*, 1973; Harvey *et al.*, 1973). Also the possibility of toxic effects described by Ehrenberg and Anderson (1954) and Manocha and Mohindra (1977) (though extremely small) from induced isotopes can be considered.

## METHOD OF CALCULATIONS

The method of calculations is essentially the same as reported earlier (Manocha & Mohindra 1976, 1977 & 1978). The total amount of sulphur, potassium and chlorine present in the body of 70 Kg standard man are respectively 175 grams, 140 grams and 105 grams and have been taken from Spiers (1968). The main isotopes of sulphur ($^{32}$S–95.1%), potassium ($^{39}$K–90.08%) and ($^{35}$Cl–75.4%) and have taken to be 100 per cent for the present estimates.

## RESULTS AND DISCUSSION

The computed data and dose rates to human body in rad per unit neutron flux due to the various nuclear reactions of 14.1 MeV neutrons (in the lab. system) with $^{39}$K, $^{35}$Cl and $^{32}$S are listed in Tables I, II and III respectively. The experimental values of the cross-sections have been taken from Cullen *et al.* (1976, 1977), Stehn *et al.* (1964) and Bormann *et al.* (1974). The experimental values listed without $\pm$ error have been taken either from graphical plots or their errors are not mentioned in the original references. The computed cross-sections particularly for ($n$, $\alpha$) reactions of light nuclei are off by a factor of 2 or 3 or sometimes more. This is because of the inadequacy of the compound nucleus theory (Manocha & Mohindra, 1973; Wadhwa *et al.*, 1974; Wadhwa & Mohindra, 1975). At present no theory gives accurately 14 MeV neutron partial cross-sections. Therefore, for dose estimates experimental values of cross-sections for ($n$, $\alpha$) reactions have been used here. For other nuclear reactions, the total dose *via* each isotope does not differ much from the dose calculated using experimental values of cross-sections.

TABLE I

| Sr. No. | Nuclear reaction | Calculated Q value in MeV | Calculated cross-section in mbs. | Experimental cross-sec. in mbs near 14 MeV. | Computed peak energy of the emitted particle $E$ in MeV | Computed dose to body in rad per unit neutron flux. |
|---|---|---|---|---|---|---|
| 1. | $^{39}$K ($n,n,$) $^{39}$K | 0 | 630.7 | 850 | 2.5 | $11.9\times10^{-14}$ |
| 2. | $^{39}$K ($n,nn$) $^{38}$K | —13.08 | 1.0 | $2.5\pm0.3$ | 0.5 | $0.03\times10^{-14}$ |
| 3. | $^{39}$K ($n,np$) $^{38}$Ar | —6.37 | 482.8 | $186\pm28$ | 3.9 | $102.6\times10^{-14}$ |
| 4. | $^{39}$K ($n,n\alpha$) $^{35}$Cl | —7.21 | 5.6 | 25 | 5.0 | $1.1\times10^{-14}$ |
| 5. | $^{39}$K ($n,p$) $^{39}$Ar | +0.22 | 333.7 | 354+54 | 5.0 | $86\ 2\times10^{-14}$ |
| 6. | $^{39}$K ($n,pn$) $^{38}$Ar | —6.37 | 205.3 | — | 2.3 | $5.4\times10^{-14}$ |
| 7. | $^{39}$K ($n,pp$) $^{38}$Cl | —10.50 | <1 | — | 1.5 | — |
| 8. | $^{39}$K ($n,p\alpha$) $^{35}$S | —6.60 | 2.0 | — | 4.5 | $0.1\times10^{-14}$ |
| 9. | $^{39}$K ($n,\alpha$) $^{36}$Cl | +1.36 | 199.0 | $84\pm12$ | 10.0 | $41.9\times10^{-14}$ |
| 10. | $^{39}$K ($n,\alpha n$) $^{35}$Cl | —7.21 | 4.8 | — | 1.5 | $0.03\times10^{-14}$ |
| 11. | $^{39}$K ($n,\alpha p$) $^{35}$S | —6.60 | 13.2 | — | 1.5 | $0.3\times10^{-14}$ |
| 12. | $^{39}$K ($n,\alpha\alpha$) $^{31}$P | —6.28 | 0 | $0.13\pm0.02$ | 0 | 0 |
| 13. | nat.K ($n,n$) (Elastic) | | | $1038\pm57$ | 0.69 (recoil) | $35.4\times10^{-14}$ |

TABLE II

| Sr. No. | Nuclear reaction | Calculated $Q$ value in MeV | Calculated cross-sec. in mbs | Experimental cross-sec in mbs near 14 MeV | Computed peak energy of the emitted particle in MeV | Computed dose body in rad per unit neutron flux |
|---|---|---|---|---|---|---|
| 1. | $^{35}Cl$ $(n,n)$ $^{35}Cl$ | 0 | 499.4 | | 3.2 | $9.5\times10^{-14}$ |
| 2. | $^{35}Cl$ $(n,nn)$ $^{34}Cl$ | −12.73 | 1.0 | 3.4±1.5 | 0.5 | $0.03\times10^{-14}$ |
| 3. | $^{35}Cl$ $(n,np)$ $^{34}S$ | −6.37 | 349.4 | — | 3.5 | $59.7\times10^{-14}$ |
| 4. | $^{35}Cl$ $(n,n\alpha)$ $^{31}P$ | −6.99 | 8.3 | — | 3.0 | $1.3\times10^{-14}$ |
| 5. | $^{35}Cl$ $(n,p)$ $^{35}S$ | +0.62 | 192.8 | 125±38 | 5.5 | $47.9\times10^{-14}$ |
| 6. | $^{35}Cl$ $(n,pn)$ $^{34}S$ | −6.37 | 95.0 | — | 2.5 | $2.3\times10^{-14}$ |
| 7. | $^{35}Cl$ $(n,pp)$ $^{34}P$ | −10.68 | <1 | — | — | — |
| 8. | $^{35}Cl$ $(n,p\alpha)$ $^{31}Si$ | −7.69 | <1 | — | — | — |
| 9. | $^{35}Cl$ $(n,\alpha)$ $^{32}P$ | +0.93 | 416.8 | 121±20 | 9.2 | $49.0\times10^{-14}$ |
| 10. | $^{35}Cl$ $(n,\alpha n)$ $^{31}P$ | −6.99 | 26.20 | — | 1.5 | $2.3\times10^{-14}$ |
| 11. | $^{35}Cl$ $(n,\alpha p)$ $^{31}Si$ | −7.69 | <1 | — | — | — |
| 12. | $^{35}Cl$ $(n,\alpha\alpha)$ $^{28}Al$ | −8.93 | 0 | — | 0 | 0 |
| 13. | $^{35}Cl$ $(n, n)$ $^{35}Cl$ (elastic) | | 950 (estimated) | | 0.76 (Recoil) | $29.8\times10^{-14}$ |

TABLE III

| Sr. No. | Nuclear reaction | Calculated $Q$ value in MeV | Calculated cross-sec. in mbs | Experimental cross-sec. in mbs near 14 MeV | Computed peak energy of the emitted particle $E$ in Mev | Computed dose to body in rad per unit neutron flux |
|---|---|---|---|---|---|---|
| 1. | $^{32}S$ $(n,n)$ $^{32}S$ | 0 | 232.2 | 400 | 4.5 | $9.4\times10^{-14}$ |
| 2. | $^{32}S$ $(n,nn)$ $^{31}S$ | −15.10 | 0 | — | 0 | 0 |
| 3. | $^{32}S$ $(n,np)$ $^{31}P$ | −8.86 | 60.0 | 105±25 | 2.5 | $10.2\times10^{-14}$ |
| 4. | $^{32}S$ $(n,n\alpha)$ $^{28}Si$ | −6.95 | 100.9 | | 4.5 | $39.9\times10^{-14}$ |
| 5. | $^{32}S$ $(n,p)$ $^{32}P$ | −0.93 | 142.2 | 225±25 | 5.3 | $63.1\times10^{-14}$ |
| 6. | $^{32}S$ $(n,pn)$ $^{31}P$ | −8.86 | 15.9 | — | 2.0 | $3.3\times10^{-14}$ |
| 7. | $^{32}S$ $(n,pp)$ $^{31}Si$ | −9.55 | 0.1 | — | 3.0 | $0.03\times10^{-14}$ |
| 8. | $^{32}S$ $(n,p\alpha)$ $^{28}Al$ | −10.79 | 0 | | 0 | 0 |
| 9. | $^{32}S$ $(n,\alpha)$ $^{29}Si$ | +1.53 | 688.8 | 109±16 | 10.0 | $87.5\times10^{-14}$ |
| 10. | $^{32}S$ $(n,\alpha n)$ $^{28}Si$ | −6.95 | 50.0 | — | 1.5 | $8.1\times10^{-14}$ |
| 11. | $^{32}S$ $(n,\alpha p)$ $^{28}Al$ | −10.79 | 0 | — | 0 | 0 |
| 12. | $^{32}S$ $(n,\alpha\alpha)$ $^{25}Mg$ | −9.50 | 0 | — | 0 | 0 |
| 13. | $nat_S$ $(n,n)$ (Elastic) | | | 910±50 (elemental) | 0.83 (recoil) | $56.9\times10^{-14}$ |

The gamma dose to human body due to the induced activity of residual nuclei in the human body (standard man of 70 kg weight) per sec. per unit neutron flux is about : $^{38}K$–$3\times10^{-17}$ m rad, $^{31}Si$–$8\times10^{-19}$ m rad and beta dose is about $^{38}K$–

$6 \times 10^{-16}$ m rad, $^{35}S$–$3.5 \times 10^{-19}$ m rad, $^{32}P$–$6 \times 10^{-17}$ m rad and $^{31}Si$–$1.5 \times 10^{-16}$ m rad.

From the survey of various listed values of experimental cross-sections for neutrons near 14 MeV, there is an overall uncertainty of about 10 per cent in their values. The peak of the evaluated spectra has been taken to be the average energy of the emitted particles. Therefore, there is an uncertainty of about 15 per cent in the evaluated average energies of the emitted particles. Thus there is an uncertainty of about 18 per cent in these dose estimates. But this uncertainty is certainly better than ignoring the contributions of these heavier nuclei (in comparison to H, C, N, O) whose recoils may have quite high quality factors (Spiers, 1968).

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