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GAMMA DOSE CALIBRATION WITH THERMOLUMINISCENT DETECTORS IN INTENSE FISSION NEUTRON FIELDS [a]

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Abstract

We present a method to estimate the gamma dose in a neutron field using a parametrization of the measured doses. The source for the high neutron fluences was the ITN-ΣΣ facility, an uranium multishell sphere placed in the thermal column of the VVRS reactor of IAP Bucharest, which has a high precision neutron fluence calibration (4%) and a very well defined neutron spectrum. The photon spectrum inside ΣΣ, degraded by absorbtion and Compton scattering was simulated by Monte Carlo method. The doses, up to $1.5 \cdot 10^4$ rad, were measured within 15% accuracy with thermoluminiscent detectors (TLDG MgF_2(Mn) and CaF_2) calibrated up to 8 MeV with radioactive sources and in the bremsstrahlung radiation of the IAP–Bucharest linear electron accelerator. A rough model to separate the contribution of prompt gamma and delayed gamma is used to calculate with 10% accuracy the doses for fluences up to $10^{15} n/cm^2$ and for different time characteristics of irradiation. For the ΣΣ facility, the ratio between the prompt gamma dose and the neutron fluence is $(1.73 \pm 0.09) 10^{-10} rad \cdot cm^2/neutron$; the contribution of the delayed gamma is less than 10% from the prompt gamma dose, depending on the time characteristics of irradiation. The method can be used to evaluate the gamma dose in any fission environment if the gamma and neutron spectra are approximately known.

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[a] Presented at the 1994 Symposium on Radiation Measurements and Applications, May 16–19, 1994, Ann Arbor, Michigan, USA

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Abstract

We present a method to estimate the gamma dose in a neutron field using a parametrization of the measured doses. The source for the high neutron fluences was the ITN-ΣΣ facility, an uranium multishell sphere placed in the thermal column of the VVRS reactor of IAP Bucharest, which has a high precision neutron fluence calibration (4%) and a very well defined neutron spectrum. The photon spectrum inside ΣΣ, degraded by absorbtion and Compton scattering was simulated by Monte Carlo method. The doses, up to $1.5 \cdot 10^4$ rad, were measured within 15% accuracy with thermoluminiscent detectors (TLDG $MgF_2(Mn)$ and CaF_2) calibrated up to 8 MeV with radioactive sources and in the bremsstrahlung radiation of the IAP-Bucharest linear electron accelerator. A rough model to separate the contribution of prompt gamma and delayed gamma is used to calculate with 10% accuracy the doses for fluences up to $10^{16} n/cm^2$ and for different time characteristics of irradiation. For the ΣΣ facility, the ratio between the prompt gamma dose and the neutron fluence is $(1.73 \pm 0.09)10^{-10} rad \cdot cm^2/neutron$; the contribution of the delayed gamma is less than 10% from the prompt gamma dose, depending on the time characteristics of irradiation. The method can be used to evaluate the gamma dose in any fission environment if the gamma and neutron spectra are approximately known.

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radiation damage studies of detectors, and so on.

Depending on the effects anticipated the irradiations can be performed in the core of a reactor or in thermal columns or secondary beams of neutrons with special properties. Usually neutrons are accompanied by a high gamma background. The evaluation of the gamma dose in an intense neutron fluence is sometimes very important for establishing the influence of the gamma background separately and to compare similar tests for different facilities.

The paper presents a method of estimation of the gamma dose in a neutron field using a parametrization of the doses measured with thermoluminiscent detectors. The choice of these detectors has been imposed by its small sensibility to the neutrons and the linear dependence of the signal with the dose which has been checked up to 4000 rad in the gamma beam of the linear electron accelerator of Institute for Atomic Physics Bucharest.

The gamma dose estimation for high neutron fluences has been performed for the ITN-ΣΣ facility, an uranium multishell sphere located inside the thermal column of the VVR-S reactor of IAP Bucharest. Its well defined neutron spectrum is close to that of the fission neutrons [1] and similar to that of the albedo neutrons in hadronic calorimeters [2]. In this way the facility is fitted for neutron damage studies of the detectors used in detection systems at high energies. The gamma dose measurements performed inside the sphere with thermoluminiscent detectors showed that the dose is smaller than in other similar facilities and is about 1.9 rad for a fluence of $10^{10} n/cm^2$.

The parameters obtained in fitting with a model described in Chapter 4 the measured doses for neutron fluences between $5 \cdot 10^{10}$ and $5 \cdot 10^{13} n/cm^2$ allowed the evaluation of the dose for fluences up to $10^{16} n/cm^2$ with a 10% precision.

2 The gamma dose inside the ITN-ΣΣ facility

The gamma spectrum for an ^{235}U target irradiated with thermal neutrons has been measured in [3] and is showed in Figure 1. Absorption and Compton scattering is responsible for its degradation. The Monte Carlo computed spectrum in the center of the sphere is represented in Figure 1, curve a. On the same figure we have drawn also the bremsstrahlung spectrum for the electron energy of 8 MeV on a target with $Z = 42$ (curve c).

For a given spectrum $\Psi_\gamma(E,t)$(photons/cm$^2 \cdot$ s $\cdot$ MeV) inside ITN-ΣΣ sphere, gamma dose is:

$$D = \int_{E_{min}}^{E_{max}} \int_0^t \epsilon(E) \Psi_\gamma(E,t) dE dt \tag{1}$$

where $\epsilon(E) = E\frac{\mu_a(E)}{\rho}$.

$E_{min} = 100$ keV is motivated by the fact that the probes and the detectors are introduced during the irradiation in 0.7 thick Sn foils. Let $f_p(E)$ the prompt fission gamma spectrum, in arbitrary units, inside the ITN-ΣΣ sphere (see Figure 1, curve a) and $f_f(E,t) = f_f(E)y(t)$ is the delayed gamma spectrum. With the condition $\int f_p(E)dE = 1$ and $\int f_f(E)dE = 1$ we have for $\Psi_\gamma(E,t) = \Psi_p(E) + \Psi_f(E,t)$ the parametrization

$$\Psi_p(E) = a\frac{F_{n,j}}{t_{i,j}}f_p(E)$$
$$\Psi_f(E) = b\frac{F_{n,j}}{t_{i,j}}f_f(E)y(t) \tag{2}$$

where:
$F_{n,j}$ is the fission neutron fluence inside the sphere in the "j" irradiation run, $F_{n,j} = \int_0^\infty \int_0^{t_{i,j}} \Psi_n(E,t)dEdt$
$t_{i,j}$ is the irradiation time in the "j" run
$\Psi_p(E)$ is the prompt gamma spectrum inside the sphere
$\Psi_f(E,t)$ is the delayed gamma spectrum
$\Psi_n(E,t)$ is the neutron spectrum in ITN-ΣΣ [1], [2]
a,b parameters

3 Thermoluminiscent detectors

We used $MgF_2(Mn)$ [4] produced by IAP Bucharest and natural CaF_2 [5] produced by INR Pitesti for the determination of the gamma dose inside ITN-ΣΣ facility.

The $MgF_2(Mn)$ detectors are small cylinders with 0.6 mm thick and 12.5 mm diameter, packed in tin sheets with 0.7 thick. The linear response with dose was tested up to 3 MeV [4] with radioactive gamma sources and up to 8 MeV at the IAP electron accelerator. We assume a maximum 20% deviation from linearity. The accuracy in the dose determination is about 10% for the individual detectors with checked efficiency. The regression in time is about 10% in a week [7].

Five natural CaF_2 tablets, each 1 mm thick and 3.2 mm in diameter are encapsulated in a protective aluminium cylinder with a 1 mm thick wall. They can measure dose between $4 \cdot 10^{-4} + 10^3$ Gy [8], with constant efficiency in the domain of 100 keV + 3 MeV gamma-ray energy. This interval was extended up to 8 MeV in this experiment in irradiation at the IAP linear accelerator. The errors are smaller than 20% for doses greater then 1 Gy.

All the TLDG detectors have been previously calibrated with a standard dosimetric gamma source of ^{60}Co. This calibration was checked with radioactive sources in the energy domain 0.1 + 3 MeV. An estimation based on the energy dependence of the gamma-ray absorption coefficients shows that the such calibrated detectors indicate, in the bremsstrahlung field of the 8 MeV electrons on a $Z = 42$ target, a dose which is 6% less than the calculated dose, for the $MgF_2(Mn)$ detectors, and 9% less for the CaF_2 detectors. So, we assume a systematical error of 6 + 8% for the gamma dose measurement inside the ITN-ΣΣ sphere.

The mean value of dose in air in the bremsstrahlung field of 8 MeV and 5 MeV electrons on $Z = 42$ target obtained with four $MgF_2(Mn)$ and five CaF_2 detectors are shown in Figure 2 versus the same doses in air measured with a calibrated ionization chamber. We assumed the 8 + 12 % errors of the each mean value for the $MgF_2(Mn)$ detectors and the 12 + 20 % errors for the CaF_2 detectors.

The KERMA for the CaF_2 and $MgF_2(Mn)$ detectors, averaged on ΣΣ neutron spectra [1], [2], using the reference [9] is $(0.905\pm0.050)10^{-10} rad{\cdot}cm^2/neutron$ and $(1.2 \pm 0.1)10^{-10} rad \cdot cm^2/neutron$, respectively. For the TLDG–FLi, calibrated with gamma sources, the ratio between the signal in rad and the KERMA is about 0.087 [10]. The same ratio for the TLDG CaF_2 is obtained less than 5%, for neutron with energy greater than 2.5 MeV [6]. So, the neutron contribution to dose measured in ΣΣ with CaF_2 and $MgF_2(Mn)$ detectors, calibrated in ^{60}Co gamma field is less then $0.1 \cdot 10^{-10} rad \cdot cm^2/neutron$. Then, for the expected gamma dose (about $1.9 \cdot 10^{-10} rad \cdot cm^2/neutron$) in ΣΣ, the increase of the dose due to neutron field (as a systematical error) is less than 5%.

4 Parametrization of the gamma dose inside ITN–ΣΣ

We assumed that the spectrum of gamma-ray fluence, $\Phi_\gamma = \int_0^t \Psi_\gamma(E,t)\,dt$, where $\Psi_\gamma(E,t)$ is defined in Eq. (2) , may be divided in four parts, due to:
a) the prompt gamma-ray and the gamma emitted by short-lived fission fragments (with mean lifetime lower than a few minutes) :

$$\Phi_p(E) = aF_{n,j}f_p(E) \tag{3}$$

b) the gamma emitted by long-lived fission isotopes (mean lifetime more than a few minutes) when TLDG are inside the sphere:

$$\Phi_{f_1}(E) = bF_{n,j}f_f(E)(1 - \frac{1}{\lambda t_{i,j}}(1 - e^{-\lambda t_{i,j}})) = bF_{n,j}f_f(E)X_1(t_{i,j}) \tag{4}$$

c) the gamma emitted by the fission fragments in the time $t_{r,j}$ between the shut-off of the reactor and the extraction of the detectors:

$$\begin{aligned}\Phi_{f_2} &= b\frac{F_{n,j}}{\lambda t_{i,j}}f_f(E)(1 - e^{-\lambda t_{i,j}})(1 - e^{1-\lambda t_{r,j}}) \\ &= bF_{n,j}f_f(E)X_2(t_{i,j}, t_{r,j})\end{aligned} \tag{5}$$

d) the gamma emitted by the isotopes produced in the previous $j-1, j-2, ..., 1$ runs of the reactors:

$$\Phi_{fs}(E) = bf_f(E)(1 - e^{-\lambda t_{p,j}} e^{-\lambda t_{i,j}} e^{-\lambda t_{r,j}}) \sum_{k=1}^{j-1} \frac{F_{n,k}}{\lambda t_{i,k}} (1 - e^{-\lambda t_{i,k}}) e^{-\lambda t_{s,k}}$$

$$= bf_f(E) \sum_{k=1}^{j-1} F_{n,k} X_k^{'}(t_{p,j}, t_{i,j}, t_{r,j}, t_{i,k}, t_{s,k}) \qquad (6)$$

The notation in the equations (4),(5) and (6) are: $t_{r,j}$ and $t_{r,k}$ are the cooling time in run j and run k; $t_{p,j}$ is time between the introduction of the detectors in the ITN–ΣΣ sphere and the start-up of the reactor in run j; $t_{s,k} = t_{s,j-1}$ is the time between the shut-off the reactor in run $k = j-1$ and the start-up of the reactor in run j; λ is the mean decay constant of the long-lived isotopes.

If we defined the integrals

$$I_p = \int_{E_{min}}^{E_{max}} f_p(E)\epsilon(E)dE$$

$$I_f = \int_{E_{min}}^{E_{max}} f_f(E)\epsilon(E)dE \qquad (7)$$

the whole dose in the run j becomes:

$$D = \int \epsilon(E)\Phi_\gamma(E)dE$$

$$= aI_pF_{n,j} + bI_f(F_{n,j}X_1 + F_{n,j}X_2 + \sum_{k=1}^{j-1} F_{n,k}X_k^{'}) \qquad (8)$$

With $\alpha = aI_p$, $\beta = bI_f$ and $q = \frac{\beta}{\alpha} < 1$ we have:

$$D = \alpha(F_{n,j} + q(F_{n,j}X_1 + F_{n,j}X_2 + \sum_{k=1}^{j-1} F_{n,k}X_k^{'})) \qquad (9)$$

5 Results

We present in Figure 3 the gamma doses in ΣΣ measured with $MgF_2(Mn)$ detectors, with 10% statistical errors, in different runs of the VVRS reactor. The doses measured with CaF_2 detectors, with 15 ÷20% accuracy, are in agreement with the doses measured with $MgF_2(Mn)$ detectors, but have a larger spread (see Figure 3).

The obtained fit values are:
$\alpha = (1.73 \pm 0.09)10^{-10} rad \cdot cm^2/neutron$

$q = 0.27 \pm 0.10$
$\lambda = (8.1 \pm 5.7)10^{-3} min^{-1}$
and $T_{1/2} = (850 \pm 600)$ min. The ratio between the prompt gamma dose and the neutron fluence inside the ΣΣ facility is $1.73 \cdot 10^{-10}$ $rad \cdot cm^2/n$; the contribution of the delayed gamma dose is less then 10% of the prompt gamma dose, depending of the time characteristics of the irradiation. For our irradiation, the mean ratio between the whole gamma dose and the neutron fluence was $1.91 \cdot 10^{-10} rad \cdot cm^2/n$ in agreement with the Mol(Belgium)-ΣΣ result [2].

The method can be used to evaluate the gamma dose in any fission environment, if the gamma and neutron spectra are roughly known.

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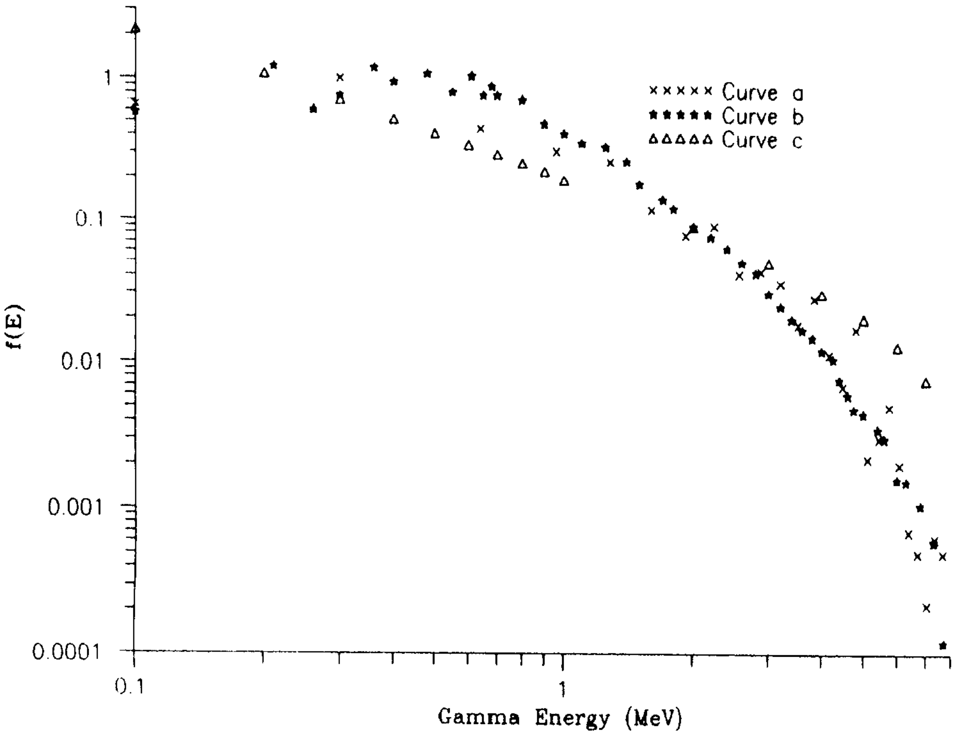

Figure 1. a) Monte Carlo prompt gamma spectrum in the center of ΣΣ
b) Prompt gamma spectrum for ^{235}U irradiated with thermal neutrons (3)
c) Bremsstrahlung spectrum of 8 MeV electrons (Z=42)

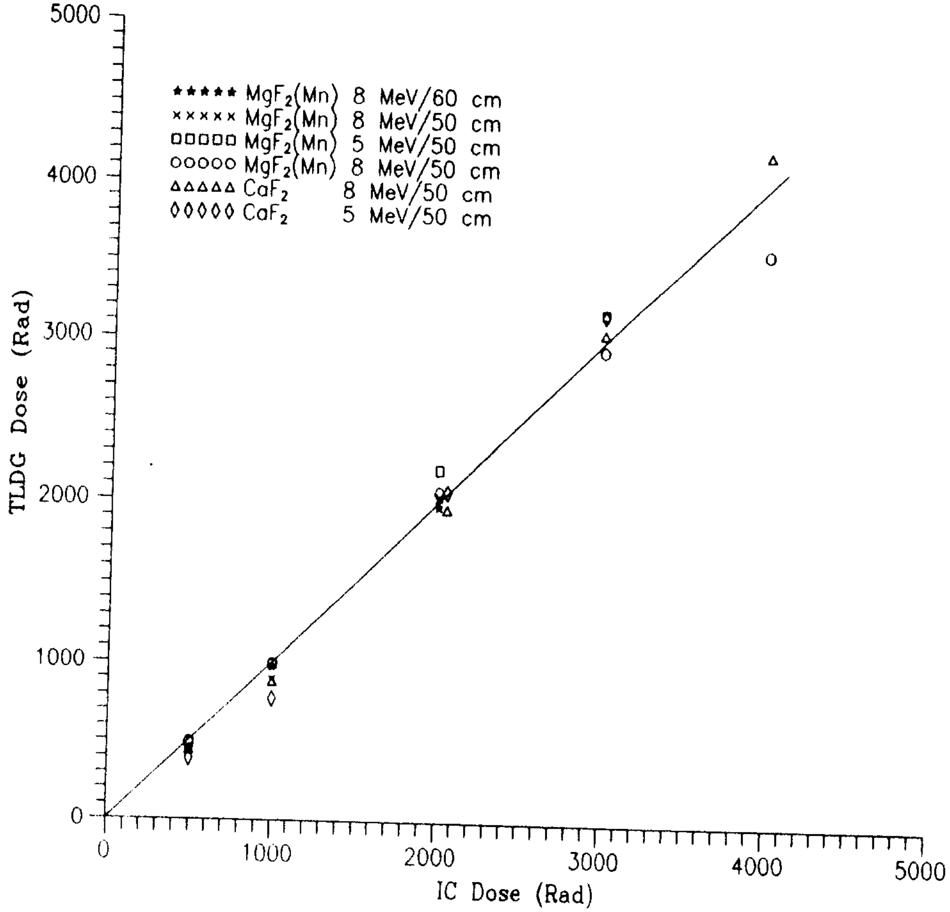

Figure 2 The doses measured with TLDG and IC in the bremsstrahlung field of 8 MeV and 5 MeV electrons at different distances

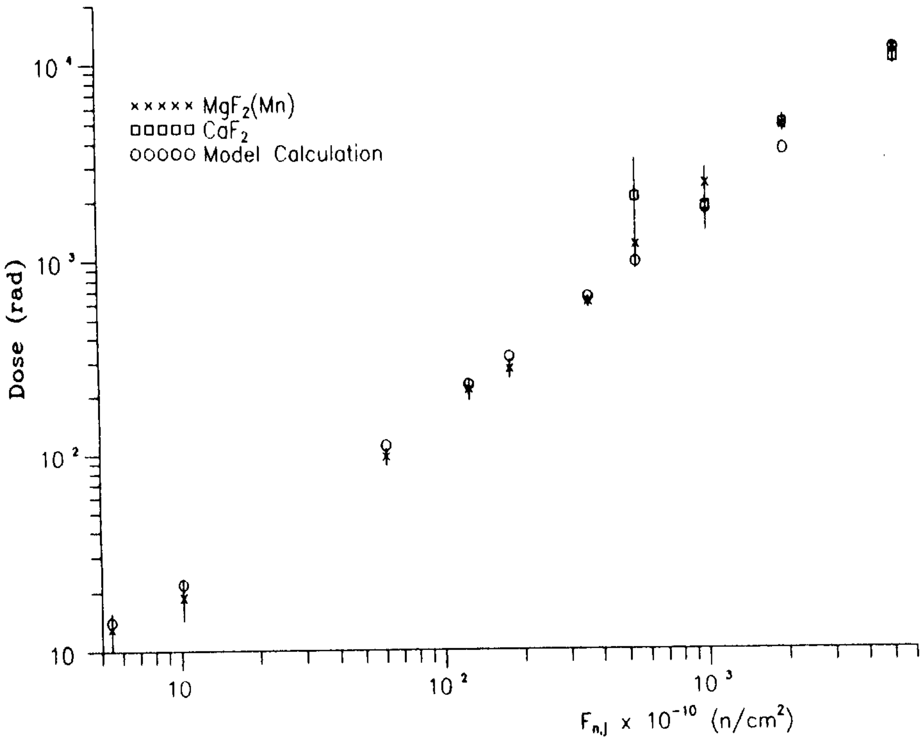

Figure 3 Gamma doses inside the ΣΣ facility