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ScienceDirect
Radiation Measurements 43 (2008) 1044–1048
Radiation Measurements
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Electronic personal neutron dosemeters for energies up to 100 MeV: Calculations using the PHITS code

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Abstract

Measurements and calculations of pulse height spectra induced by normally incident neutrons with energies between 144 keV and 100 MeV in silicon have been performed with the PTB prototype personal neutron dosemeters DOS-2002 and DOS-2005, based on silicon detectors with effective thicknesses of 40 and 5.6 μm, respectively. This work describes calculations using the PHITS code and compares measured and calculated pulse height spectra and personal dose equivalent responses. Measurements and calculations agree on an absolute scale by a factor better than 2. The personal dose equivalent response of the prototype personal neutron dosemeter DOS-2005 is much flatter than that of the DOS-2002 in the neutron energy range investigated.

Keywords: Neutron dosemeter; Pulse height spectrum; Transport code

1. Introduction

The experimental determination of dosemeter responses for high-energy neutrons is quite a complex task, since for neutrons with energies higher than 20 MeV, no monoenergetic calibration fields are available. Therefore, the response of some electronic personal neutron dosemeters was determined in fields with broad spectral distributions, in which only roughly a third of the fluence contributed to a high-energy peak. The corresponding monoenergetic high-energy neutron response has been obtained by using the knowledge of the dosemeter response for the low-energy region and then performing a complex unfolding algorithm (Luszik-Bhadra, 2007). In this way, it was shown that dose equivalent responses of the investigated silicon detector-based personal dosemeters for mixed neutron/photon fields (Thermo EPD-N2, ALOKA PDM-313, and the PTB prototype dosemeter DOS-2002) were by a factor of about 7–12 too high for neutrons having an energy of about 60 MeV. Since at such workplaces as, e.g., high-energy accelerators and aircrafts at high-flight altitudes and in space, neutrons with energies up to 200 MeV contribute appreciably to the dose, the dosemeter response must be known for higher energies. Besides, since the recent data available up to 60 MeV indicate high over-responses, the dosemeters need to be optimised. As the experimental method is, however, quite complicated, a fast optimisation of the dosemeters for the high-energy neutrons is not possible. On the other hand, powerful Monte Carlo codes have recently become available which can facilitate the developments, but of course need to be compared with measurements in order to check their reliability. This work describes the calculations of pulse height spectra in silicon by means of the PHITS code for dosemeter prototypes developed at the PTB and compares the calculated pulse height spectra with the measured ones.

2. The PHITS code

The PHITS code (Iwase et al., 2002; Niita et al., 2006) is based on the high-energy hadron transport code NMTC/JAM and incorporates the MCNP code for low-energy neutron transport and the JAERI quantum molecular dynamics model (JQMD) for simulating nucleus–nucleus collisions. It can

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1350-4487/$ - see front matter
doi:10.1016/j.radmeas.2007.10.047

handle the transport and interactions of neutrons, photons, protons, nuclei, baryons, mesons and electrons over a wide energy range up to 200 GeV. In the past, it has been successfully used for the calculation of particle fluences in space and behind the thick shielding of high-energy accelerators. Recently, it has also been used to calculate the pulse height spectra registered in a parallel-plate avalanche detector covered by neutron converters (Nakhostin et al., 2007).

3. The prototype dosemeter DOS-2002

The calculations and measurements were performed with neutrons normally incident to the PTB prototype dosemeter DOS-2002 mounted onto a $30 \times 30 \times 15\,\mathrm{cm}^3$ ISO-water phantom.

The measurements of the pulse height spectra were performed by irradiating the dosemeter in quasi-monoenergetic neutron fields produced by the PTB accelerator with energies of 144, 250, 565 keV, 1.2, 2.5, 5.0 and 14.8 MeV, and in a high-energy neutron field produced at the iThemba Laboratory for Accelerator-Based Sciences (TLABS) near Cape Town, South Africa. The spectral distribution of the latter neutron field is characterised by a high-energy peak, containing about one-third of the total fluence at 100 MeV, and a low-energy continuum, containing about two-thirds of the fluence (all fields are described in Nolte et al., 2004). In all cases, the pulses of the dosemeter prototype were additionally amplified and recorded using a multichannel pulse height analyser. The energy calibration is based on pulse heights of α-particles emitted by a ^{241}Am alpha source positioned in front of the dosemeter diode.

Fig. 1 shows the simplified set-up as it was used during the calculation. A dosemeter probe was modelled by taking into account the most sensitive parts for neutron detection. It consists of a silicon detector having a circular area of $1\,\mathrm{cm}^2$ and an effective thickness of $40\,\mu\mathrm{m}$ which is covered at the front by a combined ^{6}LiF/PE converter and surrounded by boron plastics (Luszik-Bhadra et al., 2004).

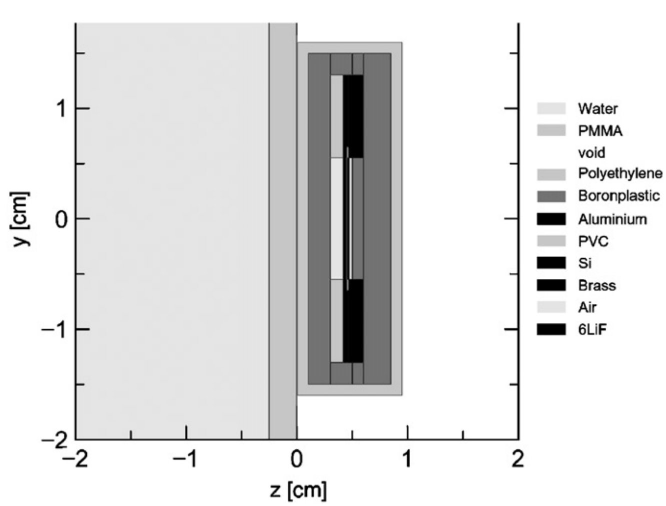

Fig. 1. DOS-2002 dosemeter probe on ISO-water phantom.

In all cases, PHITS calculations have been performed using the "Event Generator Mode (PHITS version 2.12, e-mode = 1, icntl = 0). PHITS uses libraries in the energy region emin < energy < dmax. This option has been used by setting low values of emin (zero for neutrons, 1×10^{-6} MeV for protons, deuterons, tritons, ^{3}He, alpha and nucleus, 1×10^{-3} MeV for electrons, positrons and photons) and almost maximum possible values for dmax (99 MeV for neutrons, 1000 MeV for electrons, positrons and photons). Detailed information of the level structure near the ground state is used for particle and photon emission by using the file(14) = trxcrd and igamma = 1. Additional parameters used within the calculation were deltc = 1.021e − 4 and delt0 = 1.022e − 4 (mesh of flight path), ides = 0 (create electron or bremsstrahlung-photon) and emcpf = 100 000 MeV (threshold energy for neutron capture).

A cylinder-type (s-type = 1) flat source was positioned at the border of the irradiation room, centred opposite to the dosemeter frontal surface and using normal incidence (dir = −1). For neutrons incident at energies below 2 MeV, a radius of 5.642 cm (source area $100\,\mathrm{cm}^2$) was used, in order to take into account the signals of neutrons backscattered from the phantom. At higher energies—with less significant neutron backscattering—a radius of 1.784 cm (source area $10\,\mathrm{cm}^2$) was used.

Pulse height spectra were calculated for neutrons with energies ranging from thermal to 100 MeV, using the T-deposit tally.

Fig. 2 shows the results for neutrons with an energy of 565 keV. The calculated pulse height spectra agree sufficiently well with the measured pulse height spectra on an absolute scale for pulse height signals above 400 keV. A higher number of measured pulse height signals below 400 keV can be assigned to signals from a small photon contribution in these neutron fields. The dashed region corresponds to the pulse-height range in which pulses were recorded for the determination of the personal dose equivalent $H_\mathrm{p}(10)$ for neutron radiation. A high threshold (1.25 MeV) was used in order to efficiently eliminate signals from photon radiation (see Luszik-Bhadra et al., 2004).

Fig. 3 shows the calculated particle-resolved pulse height distribution for neutrons with an energy of 565 keV. The pulse height signals are chiefly due to recoil protons produced in the PE converter and to tritons from the ^{6}Li(n,α)t-reaction in

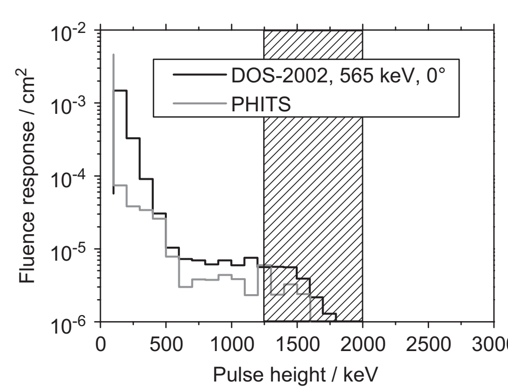

Fig. 2. Measured (black line) and calculated (grey line) pulse height spectra for 565 keV neutron radiation.

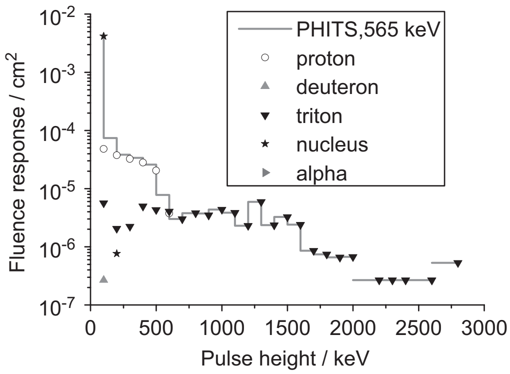

Fig. 3. Detailed calculated pulse height spectra for 565 keV neutrons.

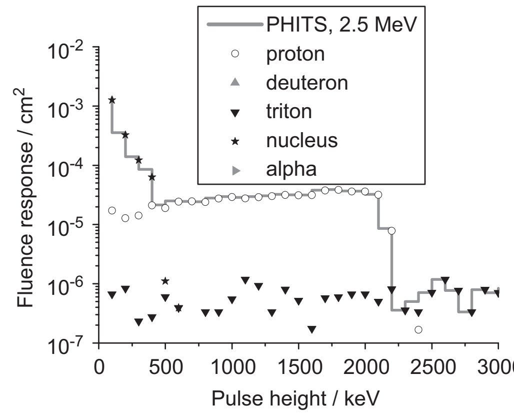

Fig. 5. Detailed calculated pulse height spectra for 2.5 MeV neutrons.

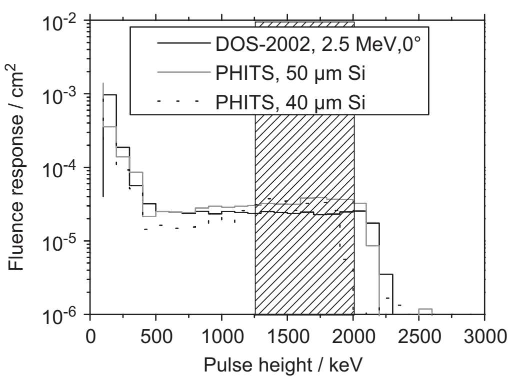

Fig. 4. Measured (black line) and calculated (dashed and grey lines for a silicon diode with an effective layer of 40 and 50 µm, respectively) pulse height spectra for 2.5 MeV neutrons.

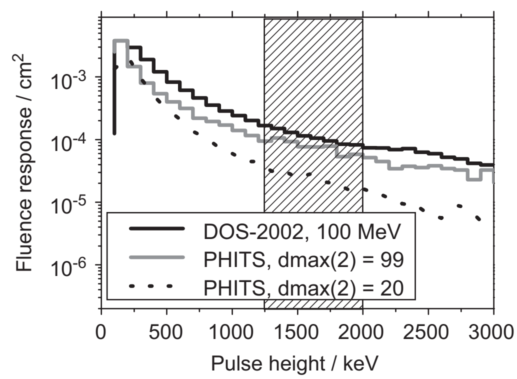

Fig. 6. Measured (black line) and calculated (grey line for dmax(2) = 99 MeV and dashed line for dmax(2) = 20 MeV) pulse height spectra for neutrons peaked in energy at 100 MeV (see text).

the ^{6}LiF converter. The recoil protons have maximum energies of about 500 keV, as expected from kinematics. Tritons with a maximum energy of 2.7 MeV and alphas with a maximum energy of 2 MeV are produced by thermalised neutrons via the ^{6}Li(n,α)t-reaction. Within the converter, all alpha particles are stopped and the tritons are degraded to a maximum energy of about 2 MeV (see Fig. 3).

Figs. 4 and 5 show the results for neutrons with an energy of 2.5 MeV. The measured pulse height spectrum shows that pulses with a maximum energy of 2.2 MeV are recorded. Thus, protons with the maximum recoil energy (2.5 MeV) are not fully stopped inside the effective layer of the detector. We found that calculated pulse height spectra agreed better to measured ones for an effective thickness of 50 µm—and not for an effective silicon detector thickness of 40 µm which had been stated by the manufacturer (see Fig. 4). We therefore used this silicon detector thickness for all calculations for the DOS-2002 device.

The particle-resolved pulse height spectra for neutrons with an energy of 2.5 MeV (see Fig. 5) indicate that the response is chiefly due to recoil protons and to heavily charged recoil nuclei ($Z > 2$). Tritons too contribute, but to a lower extent. Their maximum deposited energies are—due to kinematics—higher than those induced by 565 keV neutrons.

Fig. 6 shows the result of a recent measurement in the high-energy neutron field, peaked at 100 MeV (this is only a preliminary evaluation; uncertainty of the fluence determination: about 30%). Two simulation spectra are shown. One calculation, with $\mathrm{dmax}(2) = 99$ MeV, uses evaluated nuclear cross-section data for neutrons up to 99 MeV, coupled with an evaporation mode which is—in principle—only valid for reactions with energies below 20 MeV. The other calculation, with $\mathrm{dmax}(2) = 20$ MeV, uses for neutrons above 20 MeV the intranuclear cascade model which is also not optimal for the energy range from 20 to 100 MeV. Thus, higher deviations between measurements and calculations are expected and also found. The agreement with the measurements is better for the first case and has therefore in the following been used for the calculation of the dose equivalent response.

Fig. 7 shows the personal dose equivalent response of the DOS-2002 prototype dosemeter as a function of the neutron energy. The values were obtained by integrating the number of counts per unit neutron fluence in the pulse height intervals, as shown in the figures above, and dividing them by fluence-to-personal dose equivalent coefficients of the respective neutron radiation field (ICRU 57, 1998). Since for neutron energies above 20 MeV, these coefficients are not available at

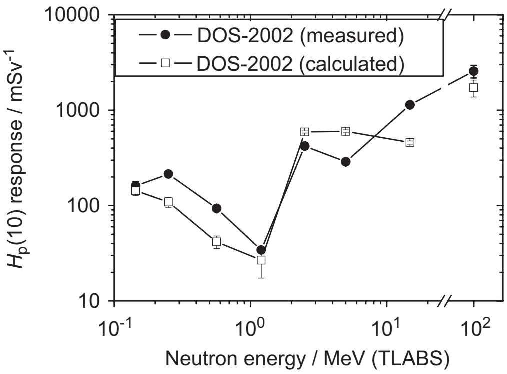

Fig. 7. Measured (full symbols) and calculated (open symbols) personal dose equivalent response as a function of the neutron energy for the DOS-2002. For the calculations, only statistical uncertainties (standard uncertainty, $k = 1$) are indicated.

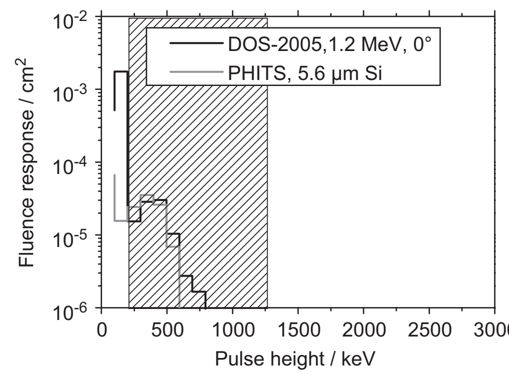

Fig. 8. Measured (black line) and calculated (grey line) pulse height spectra for 1.2 MeV neutrons.

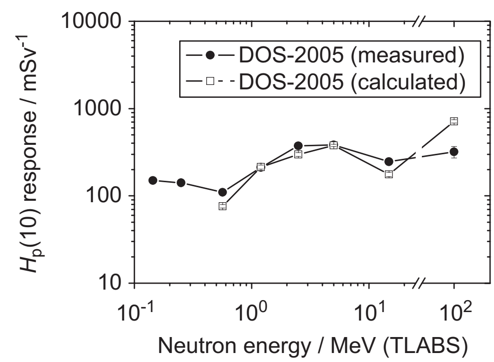

Fig. 9. Measured (full symbols) and calculated (open symbols) personal dose equivalent response as a function of the neutron energy for the DOS-2005. For the calculations, only statistical uncertainties (standard uncertainty, $k = 1$) are indicated.

the moment, the values measured in the high-energy neutron field peaked at 100 MeV were related to the ambient dose equivalent values $H^*(10)$, which can be regarded as a good approximation for $H_p(10)$ for normal incidence, since both values are defined in a similar way in 10 mm depth in a phantom consisting of tissue equivalent material and the phantom shape and dimension is expected to be fairly unimportant for high energy radiation (Sannikov and Savitskaya, 1997). The agreement of measured and calculated values is in most cases better than a factor of 2 on an absolute scale.

4. New dosemeter development DOS-2005

Recently, a new prototype dosemeter (called DOS-2005), consisting of a detector with a thin effective layer of 5.6 μm, has been set up at PTB. The detector is covered by a combined converter based on ^{6}LiF—for the detection of Albedo neutrons—and polyethylene—for the detection of fast neutrons—and surrounded by a boron plastic in a similar way as it was used for the PTB prototype dosemeter DOS-2002. But compared to the DOS-2002, a diode with a much smaller area (0.25 cm^2) and a thinner epitactic layer (5.6 μm) was used. When irradiated with 6 MeV photons, this diode showed a drastically reduced number of signals in the low pulse height region and allowed the threshold for the registration of neutron-induced signals to be set to a much lower value (0.2 MeV instead of 1.25 MeV). This led, in turn, to an improved response for neutrons in the 1 MeV region (Luszik-Bhadra, 2007).

With the DOS-2005 prototype dosemeter, measurements and calculations similar to those shown above were performed. Fig. 8 shows the measured and calculated pulse height spectra for neutrons with an energy of 1.2 MeV. Due to the thin effective layer, most of the recoil protons are not stopped, but just deposit part of their energy. An agreement of measured and calculated values similar to that for the DOS-2002 is found. The higher number of pulses measured below 200 keV can be attributed to electronic noise.

Fig. 9 shows the personal dose equivalent response as a function of the neutron energy. The measured response is flatter than that of the DOS-2002. In particular, it is drastically improved for neutrons with energies at about 1 MeV and in the neutron field peaked at 100 MeV.

5. Summary

Measurements of pulse height spectra were performed with the PTB prototype dosemeters DOS-2002 and DOS-2005, irradiated by neutrons with energies between 144 keV and 100 MeV. The PHITS code has shown good performance and the calculated pulse height spectra yielded detailed results for different charged particles. The results of the calculations agree with those of the measurements in most cases by a factor better than 2. For neutron energies between 20 and 100 MeV, the model used is not optimally suited and needs to be improved. The dosemeter DOS-2005 shows a personal dose equivalent response which is much flatter than that of the DOS-2005 in the full neutron energy range investigated.

Acknowledgements

The authors wish to thank the staff of the PTB department 6.4 and the TLABS facility for providing neutron reference fields for the measurements.

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