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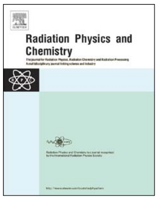

Feasibility study of an innovative active neutron dosemeter

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ABSTRACT

Prototypes of a novel pocket-sized active neutron dosemeter, based on a sensor made from the scintillator material Cs_2LiYCl_6:Ce (CLYC) coupled to a silicon photomultiplier (SiPM), were exposed to several well-characterised neutron fields produced at the National Physical Laboratory (NPL), UK.

^{6}Li-enriched CLYC is extremely interesting as a dosemeter sensor because it can detect not only gamma rays but also thermal and fast neutrons, gammas being distinguishable from neutrons by pulse shape discrimination. Thermal and low energy neutrons are detected by the ^{6}Li(n, α)^{3}H reaction, which gives rise to a well-defined peak in the pulse height spectrum. Fast neutrons typically interact via ^{35}Cl(n, p) or (n, α) reactions, and the kinetic energy of the reaction product gives rise to a pulse height spectrum that relates fairly straightforwardly to the original neutron energy spectrum. Because of this spectrometry capability, such a dosemeter has the potential to retain its accuracy to a much greater extent, compared with conventional devices, when used in radiation fields that differ from the one used for calibration.

SiPMs are low-power and compact, allowing the prototype dosemeters produced for testing to fit entirely within a standard existing personal dosemeter housing. Tests were carried out in the low-scatter neutron facility at NPL, with measurements made both on-phantom and free-in-air. The former were done to evaluate the device's performance as a personal dosemeter, and the latter to explore its potential as a very light neutron area survey meter. In this paper the experimental results are presented, performance issues encountered during the trials are discussed, and preferred application scenarios are proposed.

1. Introduction

It has long been realised that there is a need for improvements in active neutron personal dosemeters. Most radiation workers who are exposed to neutrons still wear passive devices so that the dose received is not known until the dosemeter is processed, and this can be weeks after exposure. Active (battery powered) personal neutron dosemeters, by contrast, can give a reading at any time and can sound an alarm if a dose or dose rate threshold is exceeded. However, they will usually give the wrong reading if used in a radiation field other than the one in which they were calibrated. For example, the EVIDOS project (Luszik-Bhadra et al., 2007) reported under- and over-readings by more than a factor of two for the same dosemeter in different workplace fields. This happens because such dosemeters are invariably based on silicon sensor technology, and this material differs significantly from body tissue.

Under- and over-reading are of course both undesirable, the first leading to an underestimate of health risk, and the second to unnecessary curtailment of work. There is therefore a need for new neutron sensors that have a dose response closer to that of tissue.

The National Physical Laboratory (NPL) has been undertaking a project to identify such improved sensors. External partners provide prototype sensors which are then tested in the well-characterised neutron fields available at NPL. In order to find suitable partners for this work, Hawkes (2017) carried out a survey of promising detector technologies, concentrating on sensor materials that are intrinsically more tissue-like than silicon. These include organic polymer diodes, and silicon (or preferably diamond) detectors with a surface excavated deeply at micron scales and filled with an organic material. However, although some of these technologies were pursued to the testing phase, the one found to be closest to exploitation in a practical dosemeter was, unexpectedly, a device that is not intrinsically tissue-equivalent at all.

2. The novel scintillator CLYC

The novel elpasolite scintillator Cs_2LiYCl_6:Ce (CLYC) has recently emerged as an exciting new detection medium for radiation spectrometers and dosemeters. (See, for example, Bourne et al., 2014;

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D'Olympia et al., 2012, 2014; Smith et al., 2013a.) It is sensitive to gamma rays, with a substantial photopeak relative to the Compton continuum and good resolution compared with NaI. Thermal neutrons and low energy fast neutrons are detected via the (n, α)^{3}H reaction on ^{6}Li (thermal cross section 940 barns), and high energy fast neutrons by (n, p) and (n, α) reactions on ^{35}Cl. The ^{6}Li(n, n+d) reaction also appears to be significant at neutron energies above about 2 MeV. Importantly for operation in mixed neutron and gamma fields, neutron and gamma events can be distinguished by pulse shape discrimination (PSD), for example by using the long integral / short integral approach familiar from organic scintillators (Adams and White, 1978).

For use as a sensor in a personal dosemeter, however, there are some important practical problems to address. Firstly the scintillations must be converted to an electrical signal. This would conventionally be done using a photomultiplier (PMT), but these devices are typically large, with dimensions of several cm, and require high voltage to operate. Novel photosensors such as avalanche photodiodes, PIN photodiodes or silicon photomultipliers (SiPMs) would be more suited to a low power, wearable device, but Smith et al. (2013b) found that the devices available at that time were not suitable, primarily because of their energy resolution performance. Secondly, a significant degree of signal processing is required in order to implement PSD reliably; and thirdly, further processing is needed to produce an output corresponding to the accepted dose quantities.

3. The prototype dosemeter

A prototype dosemeter based on a CLYC crystal has been developed to fit inside a standard Thermo Scientific RadEye housing (Fig. 1). The crystal is 1.25×1.25×3.1 cm^3 in size. SiPM technology has developed since the assessment by Smith et al. (2013b) mentioned above, and it has proved possible to use such a device in place of a PMT, with considerable benefits in terms of low power and compactness. In the prototype the SiPM is a 6×6 mm^2 Microfc device manufactured by SensL Technologies Ltd., and is coupled to the crystal using optical glue. The lithium in the CLYC is enriched to 95% in ^{6}Li in order to enhance the response to thermal neutrons and to low energy neutrons (up to a few hundred keV) via the ^{6}Li(n, α) reaction. PSD is used to separate neutron events from gamma events, and the corresponding pulse height spectra are accumulated and stored separately. The prototype includes a user interface with count rate display, and a contactless readout system that allows the stored spectra to be transferred to a desktop PC for offline analysis. The dimensions of the dosemeter are 10.5×6.5×3.5 cm approximately, and its weight is about 200 g. Power is provided by standard alkaline batteries within the housing, and these last for several days of continuous operation.

Fig. 1. Experimental CLYC dosemeter, using the hardware of a spectroscopic personal radiation detector for gamma and neutron radiation. The instrument is photographed against graph paper with 1-cm major divisions.

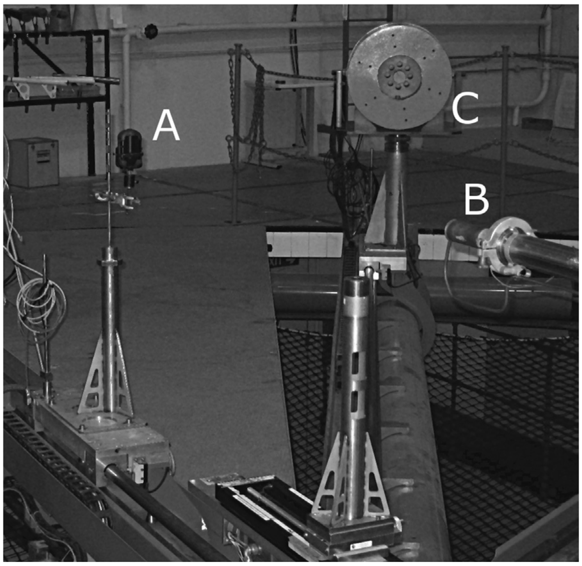

Fig. 2. The prototype dosemeter under test in the low-scatter facility of the Neutron Metrology Group at NPL. A, the dosemeter mounted free-in-air; B, the neutron-producing target of the 3.5 MV Van de Graaff accelerator; C, the long counter used to determine the fluence and dose delivered.

The dosemeter can optionally be placed inside a boron-lined holster to reduce the thermal component of the neutron field while having only a small effect on the response to fast neutrons.

4. Measurements at NPL

The prototype dosemeter was exposed to a variety of neutron fields in the low-scatter facility of the NPL Neutron Metrology Group (Fig. 2). The Group's 3.5 MV Van de Graaff accelerator was used to produce monoenergetic neutrons at several energies from 144 keV to 16.5 MeV, and radionuclide sources were used to provide standard broad-spectrum fields such as ^{252}Cf and D$_2$O-moderated ^{252}Cf. Some measurements were made with the dosemeter on-phantom, and others with it free-in-air in a lightweight cradle (designed to be held away from the body on a long handle). Where applicable a shadow cone was used to block direct neutrons from the source so that the scatter component could be measured.

In all cases the fluence rate (neutrons cm^{-2} s^{-1}) and dose rate (personal dose equivalent $H_\mathrm{p}(10)$ for on-phantom measurements, and ambient dose equivalent $H^*(10)$ for free-in-air measurements) were known to good precision, based on the known emission rates of the radionuclide sources, or the counts from a calibrated long counter (Hunt, 1976; Tagziria and Thomas, 2000).

5. Measurement results

Fig. 3 shows measurements made with quasi-monoenergetic neutrons at 3.5 MeV (spectrum (a) in the Figure) and 5 MeV (spectrum (b)). These energies were produced by directing 1.83 MeV deuterons onto a thin deuterated target, and locating the dosemeter at 70° to the deuteron beam for 3.5 MeV and 0° for 5 MeV.

The measured spectra show several peaks, and the origin of these was investigated by carrying out Monte Carlo simulations with MCNP6. The results of the calculations are also shown in the Figure. An incident neutron spectrum (including a thermal neutron component) was first calculated for the applicable measurement location using a model of the low-scatter facility, and then a second model was run in which a neutron beam with the calculated spectrum was incident on a representative 1 cm diameter sphere of CLYC. The reaction products p, α, ^{3}H and ^{3}He were tracked within the scintillator, and the total light output for each neutron interaction event was tallied using the PHL