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Absolute efficiency calibration of ^{6}LiF-based solid state thermal neutron detectors

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ABSTRACT

The demand for new thermal neutron detectors as an alternative to ^{3}He tubes in research, industrial, safety and homeland security applications, is growing. These needs have triggered research and development activities about new generations of thermal neutron detectors, characterized by reasonable efficiency and gamma rejection comparable to ^{3}He tubes. In this paper we show the state of the art of a promising low-cost technique, based on commercial solid state silicon detectors coupled with thin neutron converter layers of ^{6}LiF deposited onto carbon fiber substrates. A few configurations were studied with the GEANT4 simulation code, and the intrinsic efficiency of the corresponding detectors was calibrated at the PTB Thermal Neutron Calibration Facility. The results show that the measured intrinsic detection efficiency is well reproduced by the simulations, therefore validating the simulation tool in view of new designs. These neutron detectors have also been tested at neutron beam facilities like ISIS (Rutherford Appleton Laboratory, UK) and n_TOF (CERN) where a few samples are already in operation for beam flux and 2D profile measurements. Forthcoming applications are foreseen for the online monitoring of spent nuclear fuel casks in interim storage sites.

1. Introduction

The lack and the increasing cost of ^{3}He have triggered in the last years a worldwide R&D program investigating new techniques for neutron detection. For many applications a realistic alternative is needed to ^{3}He-based neutron detectors which so far have been the most widely used systems, as they are almost insensitive to radiation other than thermal neutrons [1–3].

Several developments involving neutron detection are currently being pursued in the fields of homeland security, nuclear safeguards, nuclear decommissioning and radwaste management. Two possible applications are worth mentioning, namely the development of neutron sensitive panels to be placed around nuclear material in a $\approx 4\pi$ solid angle coverage for coincidence neutron counting applications [4], and the deployment of arrays of small neutron detectors for the online monitoring of spent nuclear fuel storage sites [5,6].

In a previous paper [7] it was shown that the use of a fully depleted silicon detector, coupled with a ^{6}LiF neutron converter film deposited onto an independent substrate, can be successfully exploited to detect thermal neutrons with a reasonable efficiency. The neutron conversion mechanism is based on the well known reaction

$$^{6}\mathrm{Li} + n \rightarrow {}^{3}\mathrm{H}\ (2.73\ \mathrm{MeV}) + \alpha\,(2.05\ \mathrm{MeV}) \tag{1}$$

which is the only possible decay channel following the neutron capture in ^{6}Li, and is free of gamma rays. Its cross section at thermal neutron energy is 940 b, and it scales with 1/v up to ≈200 keV with a back-to-back isotropic emission of the reaction products. In Refs. [8] and [9] detailed justifications were given for the convenience of using ^{6}LiF as neutron converter material on a planar detector, which can be summarized as follows:

- higher kinetic energy of the decay products following the neutron capture in ^{6}Li, in comparison with ^{10}B even though the cross section is four times lower;
- ease of fabrication and assembling;
- robustness;
- possible reusability of the silicon diode and of the converter as independent components;
- low cost;

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- possible position sensitivity by using a single or double side silicon strip detector.

Moreover, the intrinsic detection efficiency one can achieve with this configuration, i.e. separate converter and silicon diode, is lower than, but comparable with, what is obtained by depositing the converter directly onto a micro- or nano-structured silicon diode [10], while showing basically a 100% production yield even with 25 cm^2 area detectors.

The reliability of this technique, along with a characterization in terms of response, efficiency and gamma sensitivity, was also assessed by means of GEANT4 simulations [11]. The technique is indeed well established [12,13], and several applications are already in use like for instance at the n_TOF spallation neutron beam facility [14,15]. The energy spectrum measured by the silicon detector in such a configuration has a characteristic shape, and allows to discriminate the capture reaction products from the low-energy background basically due to gamma rays. Even though we found an excellent agreement between simulation and experimental data taken with neutron sources and beams, it only concerned the spectrum shape as in all the tests performed there was only a rough knowledge of the incoming thermal neutron flux. In most applications of neutron detectors a quantitative assessment of the measured neutron flux is required, hence the need to determine the absolute efficiency of the detectors and to verify the reliability of the simulations.

In this paper we report on the intrinsic efficiency calibration of a few samples of this solid state neutron detector making use of a certified thermal neutron field, and the results are compared to the respective GEANT4 simulations.

2. Experimental setup

Neutrons cannot be constrained by means of electromagnetic fields, and they only interact with matter via elastic and nuclear reactions. Predicting their trajectories, doses and fluxes is not straightforward and needs numerical simulations, in particular for thermal neutrons. Whereas the efficiency of charged particle and gamma detectors can be easily measured by means of standard laboratory sources, this is not the case with neutron detectors. In order to measure the intrinsic efficiency of a thermal neutron detector one can: (i) place it at a given position in a generic neutron field and compare the number of counts per unit area with the same quantity as measured by a reference detector placed in the same position (relative calibration); (ii) place it in a well-known reference neutron field and calculate the ratio of the detected counts to the real number of impinging neutrons (absolute calibration). A more detailed discussion about the intrinsic efficiency, along with other calibration methods, can be found in [16].

2.1. The thermal neutron field

For the efficiency calibration of the devices we used a thermal neutron field at the Physikalisch-Technische Bundesanstalt (PTB). The Thermal Neutron Calibration Facility at PTB [17,18] consists of sixteen ^{241}Am–Be sources that are mounted inside a graphite block whose dimensions are 150 cm (height), 150 cm (width), and 180 cm (depth). The reference position is at 30 cm from the front surface of the moderator exit window and 75 cm above the floor. The neutron and photon fields at the reference position were characterized by means of measurements and Monte Carlo simulations [18]. The neutron field is highly thermalized with Maxwellian distribution, 98.4% of neutrons have energies below the cadmium cut-off energy with a thermal neutron flux at the reference position of 68.3 ± 1.9 neutrons/cm^2/s and a uniform field size of at least 10 × 10 cm^2. Optionally, a cadmium plate can be installed in front of the moderator exit window that cuts the thermal neutron contribution below the cadmium threshold. This way, a pure thermal field can be obtained by applying the difference method. However, the high-energy ($E\gamma \geq 5$ MeV) gamma ray flux increases by about one order of magnitude when the cadmium plate is inserted.

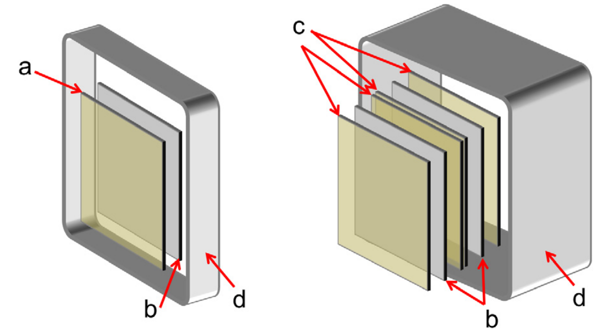

Fig. 1. The two thermal neutron detector samples calibrated at PTB. Left: SiLiF1.6 made of a 1.6 μm ^{6}LiF layer (thin converter) deposited onto a carbon fiber plate (a), coupled to a 300 μm thick silicon detector (b), and enclosed in a thin aluminum box (d). Right: SiLiF64 made of a double sandwich of four 16 μm ^{6}LiF layers (thick converters) deposited onto carbon fiber plates (c), and enclosed in a thin aluminum box (d).

2.2. The thermal neutron detectors

The thermal neutron detectors we discuss in this paper were named SiLiF, because they feature silicon detectors (3 cm × 3 cm × 300 μm) and ^{6}LiF converters. Two samples were calibrated at PTB (Fig. 1):

- A SiLiF1.6 made of a 1.6 μm ^{6}LiF layer (thin converter) deposited onto a carbon fiber plate (a), coupled to a 300 μm thick silicon detector (b), and enclosed in a thin aluminum box (d).
- A SiLiF64 made of a double sandwich of four 16 μm ^{6}LiF layers (thick converters) deposited onto carbon fiber plates (c), and enclosed in a thin aluminum box (d).

The silicon detectors we chose for our purpose are fully depleted, double sided, and have 3 cm × 3 cm × 300 μm size in order to have a reasonably large area and a comfortable detector capacitance of 300 pF, thus implying moderately low cost and no need of high performance electronics.

In Fig. 2 we show one of the calibrated detectors during the measurement in front of the Thermal Neutron Calibration Facility. The light beams from the laser alignment system are visible. The detectors were biased at 30 V, so that the silicon diodes were fully depleted. This was especially important for the SiLiF64, as the neutron converters were installed on both faces of each silicon diode and the full depletion regime is mandatory to get the same response from the front and the back sides. The operating principle is quite simple: we choose a neutron discrimination energy threshold and declare as neutrons all the counts above that threshold. Below the threshold there will be other neutron events mixed with gamma ray events and background noise. Of course the higher the threshold the cleaner the neutron signal will be, but at the same time the lower the detection efficiency will be. Therefore one has to find a trade-off between purity and efficiency, which may depend on the specific application and on the user needs.

3. Simulation procedure

The detectors were simulated by means of the well known GEANT4 toolkit [19,20], including the aluminum box, the carbon fiber substrate, the ^{6}LiF neutron converter, and the silicon diode. The supporting printed circuit board, the cable and the connector were not included in the simulation. 2 × 10^6 monoenergetic neutrons were generated for each case, with 25.3 MeV kinetic energy, uniformly and perpendicularly irradiating the detector area. A preliminary set of simulations was run in order to decide the optimal thickness for the ^{6}LiF converter. We simulated a configuration made of a single converter layer placed in front of the silicon detector, like in Fig. 1 left, but with the converter thickness varying from 8 to 16 μm in steps of 1 μm. The resulting