# Neutron detection devices with $^{6}$LiF converter layers

Paolo Finocchiaro, Luigi Cosentino, Sergio Lo Meo, Ralf Nolte, Desiree Radeck

***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 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. Several configurations were studied with the GEANT4 simulation code, and then calibrated at the PTB Thermal Neutron Calibration Facility. The results show that the measured 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.**

***Index Terms*—Thermal neutron detectors, $^{3}$He replacement, $^{6}$LiF neutron converter, silicon detectors.**

## I. 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],[2],[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 to be mentioned, 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].

This work was supported by the Istituto Nazionale di Fisica Nucleare
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In a previous paper [7] it was shown that the use of a fully depleted silicon detector, in combination with a $^{6}$LiF neutron converter film, can be successfully exploited to detect thermal neutrons with a reasonable efficiency, as also suggested by other authors [8],[9]. 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 [10]. The neutron conversion mechanism is based on the well known reaction

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

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. 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.

This technique is indeed well established [11],[12], several applications are already in use, like for instance at the n-TOF spallation neutron beam facility [13],[14]. In this paper we report on the calibration of a few samples of this solid state neutron detector in a thermal neutron field, and the results are compared to the respective GEANT4 simulations.

## II. Experimental setup

### A. The thermal neutron field

For the calibration of the devices we used the thermal neutron field at the Physikalisch-Technische Bundesanstalt (PTB). The Thermal Neutron Calibration Facility at PTB ([15],[16]) 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 facility is sketched in Fig. 1 and shown in Fig. 2. 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 [16]. The neutron field is highly thermalized, 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 x 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 ($E\gamma \geq 5MeV$) gamma ray flux increases by about 2÷3 orders of magnitude when the Cadmium plate is inserted. Fig. 3 shows the distribution of the neutron energies at the reference position, with and without the Cadmium plate.

### *B. The thermal neutron detectors*

The thermal neutron detectors we discuss in this paper were named SiLiF, because they feature silicon detectors (3 cm x 3 cm x 300 µm) and $^{6}$LiF converters. Two samples were calibrated at PTB (Fig. 4):

- 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).

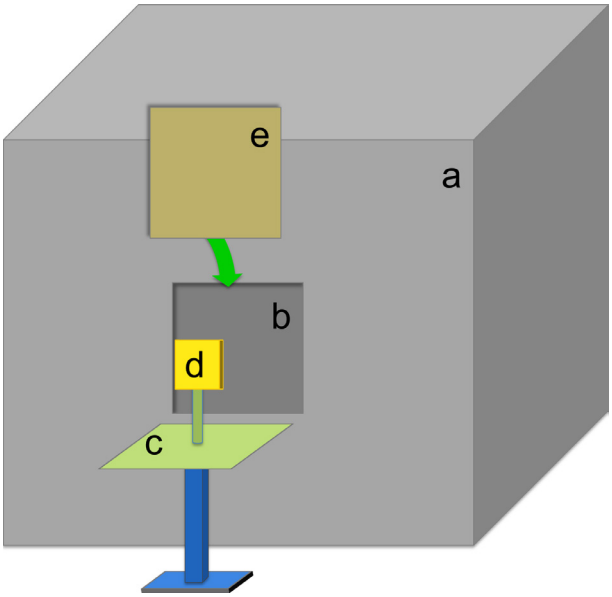


Fig. 1. Sketch of the PTB Thermal Neutron Calibration Facility. (a) The moderator/shield. (b) The neutron exit window. (c) The detector support plate. (d) Detector. (e) Optional Cadmium plate to be installed on the output window.

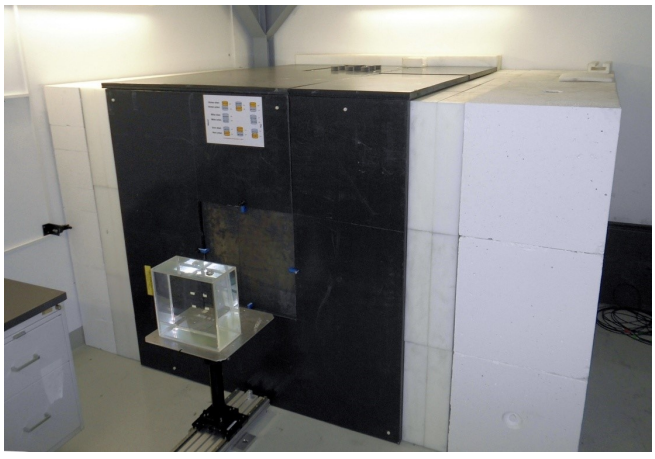

Fig. 2. A picture of the PTB Thermal Neutron Calibration Facility.

In Fig. 5 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 criterium is quite simple: we decide 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.

## III. Simulation Procedure

The detectors were simulated by means of the well known GEANT4 toolkit ([17],[18]), 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. $2x10^{6}$ neutrons were generated for each case, with 25.3 meV kinetic energy, uniformly and perpendicularly irradiating the detector area.

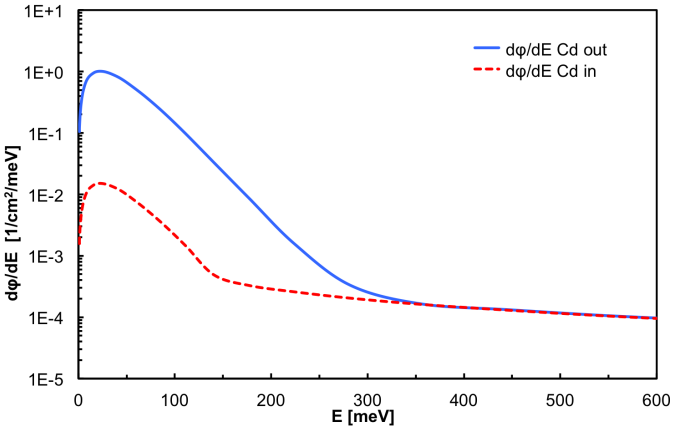


Fig. 3. Neutron energy distribution at the reference position of the PTB Thermal Neutron Calibration Facility, with and without the Cadmium plate.

## IV. Measurement Results

The triton and the alpha particle emitted from the reaction (1) following a neutron capture have well defined energies, which are degraded after crossing the residual converter layer thickness and the thin air layer between the converter face and the silicon detector. Therefore, the thinner the converter the sharper is the spectrum shape measured by the silicon detector. Indeed, by looking at Fig. 6, where we reported the energy spectrum (counting rate **ε** normalized to the unit flux) as a function of the energy, one can see that using a 1.6 µm $^{6}$LiF converter the triton and alpha contributions to the spectrum are well identified. The alpha and triton endpoint energies are easily spotted on the spectrum, and this allows a perfect energy calibration of the detector, quite useful to set

the neutron discrimination threshold with high precision. The agreement with the simulated spectrum is remarkable, considering that the experimental data were normalized to the nominal flux and therefore both spectra are in absolute units.

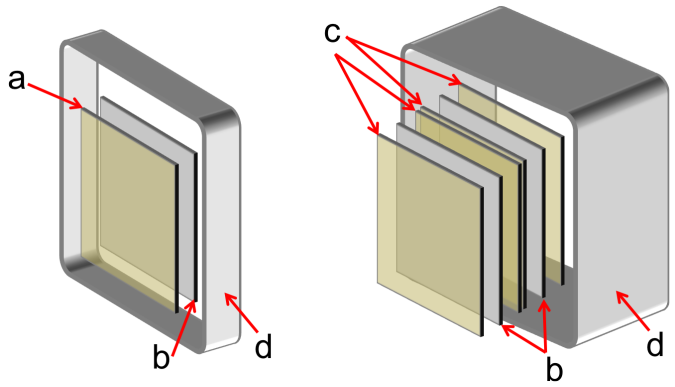


Fig. 4. The two thermal neutron detector samples calibrated at PTB. Left: SiLiF1.6 made of a 1.6 µm $^{6}$LiF layer (thin converter) deposited onto a carbon fiber plate (a), coupled to a 300 µm thick silicon detector (b), and enclosed in a thin aluminum box (d). Right: SiLiF64 made of a double sandwich of four 16 µm $^{6}$LiF layers (thick converters) deposited onto carbon fiber plates (c), and enclosed in a thin aluminum box (d).

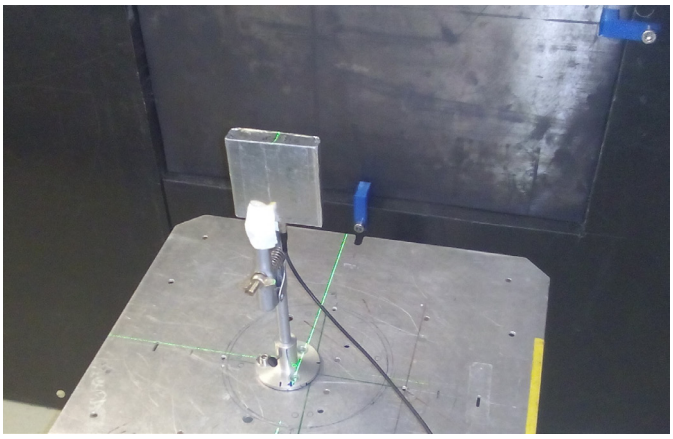

Fig. 5. One of the calibrated detectors during the measurement in front of the Thermal Neutron Calibration Facility sketched in Fig. 1. The light beams from the laser alignment system are visible.

Unfortunately with such a thin converter the neutron detection efficiency is of the order of 0.5%, quite low to allow a realistic employment of this detector. However, due to its spectral features and precision of calibration, it can be quite useful as a reference for the absolute calibration of other detectors. In Fig. 7 we show the energy spectrum as measured with the SiLiF64 detector, along with the simulation result. The agreement between simulation and measurement is remarkable also in this case, thus validating both the simulation tool and the detector behavior. In Fig. 8 we reported the energy spectra as measured by the SiLiF64 with and without the Cadmium plate installed on the exit window. The spectra were normalized to the nominal unit flux respectively with and without Cadmium plate. One can immediately see that on the one hand the neutron contribution decreases by about two orders of magnitude, whereas the gamma contribution is relevant at least up to 1÷1.5 MeV.

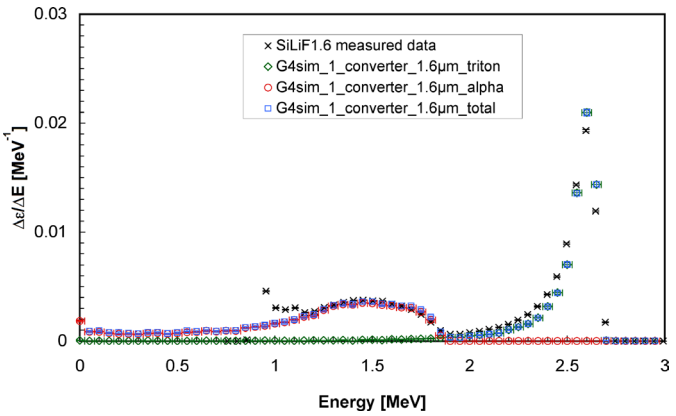


Fig. 6. Energy spectrum (counting rate ε normalized to the unit flux) measured with the SiLiF1.6 detector and compared with the simulated one. Also reported are the separate simulated contributions from alphas and tritons.

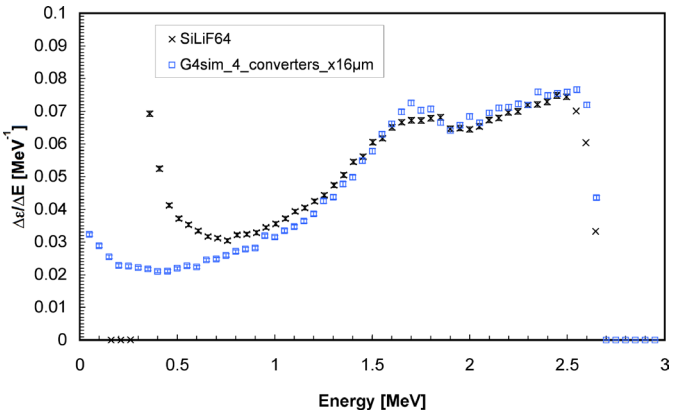


Fig. 7. Energy spectrum (counting rate ε normalized to the unit flux) measured with the SiLiF64 detector and compared with the simulated one.

Indeed, in Fig. 9 we reported the ratio between the two spectra of Fig. 8, and such a ratio shows rather clearly that in order to have a good γ/n discrimination the neutron discrimination threshold value should be chosen at 1.5 MeV. However, lower threshold values can be safely employed in applications where there are no high energy gamma rays (as a reference, the γ/n contamination probabilty from $^{60}$Co gamma rays when setting a 1.5 MeV discrimination threshold is $\leq 10^{-12}$ [10]).

TABLE I
SIMULATED AND MEASURED DETECTION EFFICIENCY

| detector | simulated efficiency | measured efficiency |
|---|---|---|
| SiLiF1.6 | 0.48 % | 0.50 ± 0.02 (syst) % |
| SiLiF64 | 8.25 % | 7.95 ± 0.35 (syst) % |

In Table I we listed the simulated and measured efficiency for the two detectors.The measured data have a low statistical uncertainty, whereas the systematic one is more relevant, especially on the SiLiF64 detector, because of the energy calibration. Indeed, while the calibration of the SiLiF1.6 can be very precise due to the presence of the two very well defined endpoints for alphas and tritons, this is not the case for a thicker converter layer, as can be easily seen by comparing Fig. 6 and Fig. 7.

Therefore the systematic uncertainty was estimated by

assuming a ±10 keV uncertainty in the alpha endpoint of the SiLiF1.6 and a ±50 keV in the alpha endpoint of SiLiF64. The results look satisfactory with a quite good agreement between data and simulations. This gives us confidence on the reliability of the simulation tool and of the detectors in view of new designs.

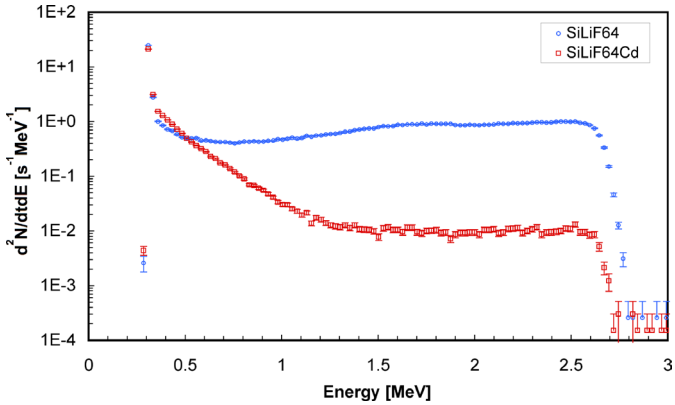


Fig. 8. Energy spectrum measured with the SiLiF64 detector, with and without the Cadmium plate.

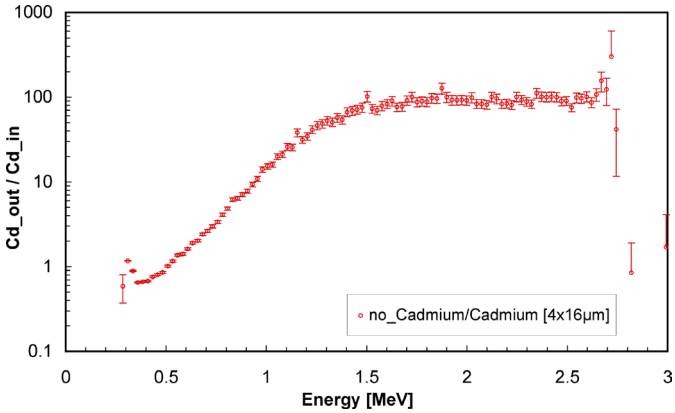


Fig. 9. Ratio between the two spectra of Fig. 8, that justifies the choice of 1.5 MeV as neutron discrimination threshold value.

## V. Perspectives

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, and to this aim a new set of simulations for several different configurations has already been started, along with additional calibrations using the same facility at PTB.

## VI. Conclusion

In order to cope with the need of new thermal neutron detectors as an alternative to $^{3}$He tubes in research, industrial, safety and homeland security applications, we have developed, tested and characterized solid state silicon detectors coupled with $^{6}$LiF neutron converters. Even though their detection efficiency is only around 8%, the gamma rejection performance and the rather low cost as compared to $^{3}$He tubes, make these detectors quite interesting for several applications, especially those with continuous monitoring purposes.

## Acknowledgment

We thank Sebastian Fässer for his invaluable support during the calibration measurements at PTB. We are strongly indebted with Carmelo Marchetta and Antonio Massara for the preparation of the $^{6}$LiF converters. A heartly felt acknowledgment is due to Marco Ripani for his constant encouragement and support within the framework of the INFN-E Strategic Project.

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