Detection efficiency study of an imaging detector for low energy neutrons

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ABSTRACT

High accuracy imaging of thermal neutrons has been demonstrated with detectors having solid converters coated with secondary electron emitters and coupled to gaseous electron multipliers. The present work concentrates on study of the neutron detection efficiency of detectors equipped with composite CsI coated ^{6}Li neutron converters. Monte Carlo simulations of the neutron conversion and the charged particle and electron emission processes permit to optimise the converter parameters. The experimental study of the detection efficiency is described in detail and the results are compared with the theoretical predictions.

1. INTRODUCTION

We have proposed a novel position sensitive neutron detector based on a solid foil converter coupled to a low-pressure multistage gas amplifier[1,2]. The charged particles, resulting from slow neutron capture process in solid converters (^{nat}Gd or/and ^{nat}Li), are detected in a low pressure multiwire proportional counter. In order to improve the spatial resolution, dominated by the long range of the charged particles in the gas, we have proposed to use a composite foil converter: the neutron converting material is coated with a thin layer of CsI, known as the best secondary electron (SE) emitting material[3,4]. Low-energy secondary electrons, induced in the CsI by the charged particles, are emitted from the converter surface in the vicinity of neutron conversion point and are immediately multiplied in the first parallel amplification gap. Theoretical investigations predict an average number of about 60 secondary electrons induced in CsI by 2 MeV emitted tritons[5]. Such tritons produce near the exit point from the converter about hundred electrons per 1 mm in 13 hPa isobutane. Both contributions, from low-energy SE and from direct gas ionisation, exist in each neutron conversion event. The surface emission of SE and the exponential nature of the amplification in the first parallel gap, lead to a very accurate localisation of the neutron conversion point, independent of the length and orientation of the charged particle track in gas[6]. The additional number of low energy electrons from the CsI should also increase the detection probability of converted neutrons.This work present an improved detector based on a ^{6}Li converter foil coupled to two low-pressure multistep proportional counters. Measured detection efficiency values are compared with theoretical predictions obtained with a Monte Carlo simulation code[7,8].

In our previous work[1,2], we demonstrated some very attractive features of a detector based on a solid composite converter foil: very good position determination, better then 0.5 mm (fwhm), free of parallax, an excellent time resolution (the arrival time of a neutron can be measured with less the 100 ns uncertainty), high count-rate capability and, in the case of a ^{6}Li converter, a very low gamma-ray background sensitivity. However, our previous detector was not equipped with an optimised converter and therefore the detection efficiency was low. Based on theoretical calculations of neutron conversion and particle escape probability from the converter foil, forward and backward, an efficiency of 25% was predicted with a ^{6}Li converter and 52% with a ^{157}Gd for neutrons of 0.2 nm wavelength. The details of these calculations will be presented elsewhere.

2. THE DETECTOR

For an experimental investigation of the attainable detection efficiency we designed the detector shown schematically in Fig.1. A CsI-^{6}Li-CsI converter foil was placed between two low-pressure multistep electron multipliers. With this sandwich arrangement we intended to take advantage of the charged particles emitted from both sides of the converter foil. The neutrons enter the detector through a 0.5 mm thick Al window, hit the converter foil and the resulting alpha particles and tritons, which escape the foil, are detected by the two avalanche counters. More details of the detector and the operation principle of the low pressure avalanche counters have been published elsewhere[1,9]. The detector is enclosed in a stainless steel vessel and was operated with isobutane at 13 hPa , in flow mode. The active surface of the detector is 65 cm^2.

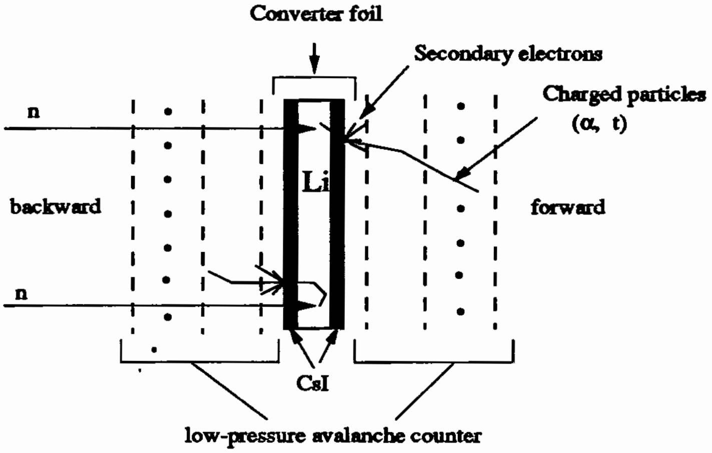

Fig. 1. Schematic drawing of the neutron detector

2.1 ^{6}Li converter foils

In the previous investigations ^{nat}Gd and ^{nat}Li were used as converter materials for the study of the general properties of this detector type. An optimised detector, however, should use converters enriched in ^{157}Gd or ^{6}Li isotopes. Due to the superior imaging properties, lower gamma-sensitivity and availability of material with higher enrichment, it was decided to continue our investigations with ^{6}Li. The converter foils were prepared by two different techniques, rolling and vacuum evaporation, from metallic Li, 95% enriched in ^{6}Li. With both methods it was difficult to obtain the required optimal thickness of 135 μm. A large area (~ 80 cm^2) evaporated foil with less then 10 % thickness difference between middle and edge (up to 3 % difference in emission probability for the neutron energy range considered here) requires a special evaporation set-up to reduce the amount of lost material and the thermal load. For rolling, the requested optimal foil is too thin, due to the lithium soft consistence.

The best converter obtained by rolling was a 150 μm thick foil, of relatively uniform thickness (6% thickness difference between edges and middle at 90 mm diameter). The foil was coated on both sides with 500 nm CsI layer, by thermal evaporation. Two stainless steel grids, 81% optical transmission , were used to provide the mechanical support. A second foil was prepared using electron beam evaporation of ^{6}Li layer deposited on an Al substrate 2 mm thick and 50 mm diameter. This was necessary because we could not prepare a self supported evaporated foil and all our attempts to use a thin polymer foil as backing failed due to the large thermal load. The best ^{6}Li layer obtained by this technique was 100 μm thick, of good uniformity. Half of its free surface was then coated with 500 nm CsI. This permitted a direct comparison of the performance with and without CsI. Due to the Al substrate, the foil could be read out only from one side, and the detector had to be rotated by 180 deg. in the beam in order to measure the „forward“ and „backward“ contributions.

During the storage, mounting and measuring time, an ageing of the ^{6}Li foil took place; it appeared mostly near the edges, in the form of wiggles, disturbing the homogeneity of the electrical field in the 2 mm preamplification gap. Consequently, the operating voltage had to be continuously reduced, as the ageing progressed.

2.2 Beam set-up

The measurements were performed at the 1 MW research reactor of the PTB- Braunschweig. The beam consisted of neutrons with wavelength up to 0.35 nm ($E_n > 6$ meV), collimated to 15 mm x 15 mm by boron and lead collimators. The neutron wavelength was determined by time-of-flight measurement (flight path of 8.8 m) with a resolution of 0.005 nm. A ^{3}He proportional counter, 98% transmission was used as monitor. The absolute neutron flux was determined by the ^{3}He proportional counter, an europium activated lithium iodide detector (LiI(Eu), 4.38% enriched in ^{6}Li) and a lithium glass scintillator (KG2L, 8.7% enriched in ^{6}Li) of known detection efficiencies.

3. RESULTS

Due to the relatively small absorption cross section for thermal neutrons in ^{6}Li (940 barn), compared with 240 000 barn of ^{157}Gd or 3000 barn of ^{3}He , it is extremely important to detect each charged particle originating from the neutron absorption in the converter and penetrating the counting gas. Our theoretical calculations , performed for a

100 μm thick lithium converter, covered with a 500 nm CsI layer, predict an average energy of the emitted particle between 1.4 and 1.8 MeV for tritons and 0.9 and 1 MeV for alpha particles, depending on the neutron absorption point. Such a particle produces some hundred ionization electrons in the first 2 mm of gas. However, if the gain in the preamplification gap is sufficiently high (10^2 to 10^3) the avalanche is dominated by the electrons produced in the first few tenths of a mm in the gas and by the SE ejected from the foil surface[5].

For theoretical estimations of the emission probabilities of the charged particles (alphas, tritons and electrons) leaving the converter foil, a special Monte Carlo code has been developed. It takes in consideration the following: slow neutrons, with energies between 1 meV and 80 meV are absorbed in a converter foil (made of gadolinium or lithium and coated with a CsI layer) according to the absorption cross section values. The transport and emission of the resulting charged particles and electrons are followed until they exit the converter. The gas processes (ionization, transport and amplification) are not included. The distribution of the number of the escaping particles, their energy and the distance between the neutron absorption point and the particle exit point, are calculated. The secondary electron emission from the CsI layer, induced by the primary charged particles, is simulated and the yields of secondary electrons are obtained. The simulation uses a new physical model describing the radiation-induced SE emission from alkali halides[7,8]. The model is free of apriori assumptions and semiempirical formulae and is based only on calculated microscopic cross-sections of electron interactions with the electronic and nuclear subsystems of the solids.

In figs. 2a-2c theoretical and experimental values of the detection efficiency with a 100 μm thick ^{6}Li foil are presented. The values of efficiency in the backward direction, with the highest attainable voltage of -805 V in the preamplification gap, (fig . 2a) are in good agreement with theoretical estimations. As can be observed from fig. 2a and 2b, the value of the premplification voltage has a strong influence on the efficiency value: a difference of only 15 to 25 V in voltage induces a 35 % drop in efficiency. In both cases an enhancement in efficiency of about 10% due to CsI coating can be seen. The detection efficiency data in the forward direction (fig. 2c) do not show the CsI contribution anymore and the measured values are 30% lower than the theoretical estimations. This is the effect of the lower preamplification voltage (-780 V) applied in the measurement. The lithium ageing process affects the foil surface and made the detector instable at high voltages. Consequently , the voltage on the pregap had to be reduced. Fig. 2d

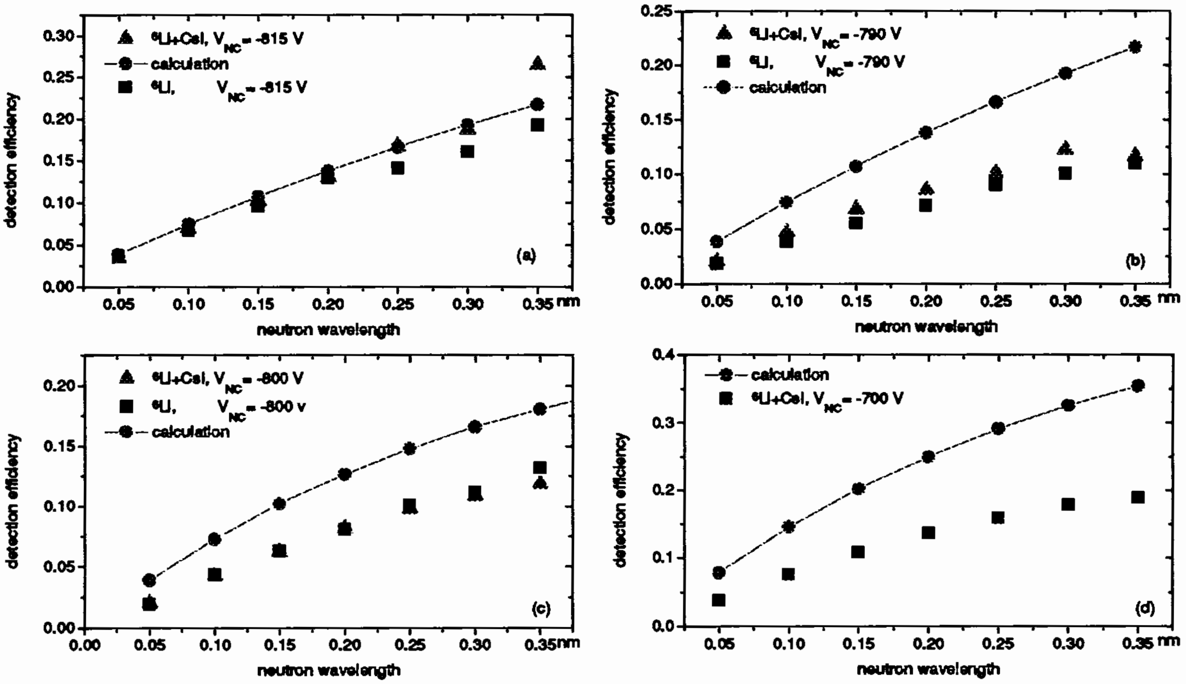

Fig. 2. Calculated escape probabilities and measured detection efficiency for: 100 μm thick ^{6}Li foil, backward (a, b) and forward (c); 150 μm thick ^{6}Li foil, backward + forward (d).

presents total (backward + forward) efficiency values obtained with the 150 μm thick foil. The experimental results represent only 50 % of the theoretically predicted values. The main reason is again the low voltage applied in the peamplification gap during this measurements, which is responsible for low and widely spread pulse-height amplitudes. This leads to a large inefficiency. The presence of the two supporting grids could account for no more than 5% efficiency reduction.

The experimental results in the backward direction indicate a contribution of the CsI coating to efficiency enhancement, provided a large amplification in the parallel gap is applied. In this case the SE emission improves the avalanche statistics, leading to narrower pulse-height spectrum and providing efficiency values which are approaching the theoretically predicted ones.

4. CONCLUSIONS

Theoretical and experimental detection efficiencies of a slow-neutron imaging detector, equipped with a composite ^{6}Li- CsI, have been presented. A total efficiency of 25 %, for 0.18 nm neutrons, was theoretically predicted for a 135 μm thick ^{6}Li -CsI converter. The efficiency measured with a 100 μm thick ^{6}Li converter foil, in the backward direction, is in a very good agreement with the theory but in the case of forward direction a difference of 35% was measured. This difference is most probably due to the low value of the preamplification voltage, in this latter measurement, imposed by the ageing of the foil. It was verified that the same difference is measured also in the backward direction, when using the same voltages. Part of our results, namely the efficiency values in backward direction and the pulse height-spectra, indicate a contribution from the CsI coating. It should be remarked that the principal role of the CsI coating is the improvement in localisation and timing properties[1]. However, unlike other methods, which often improve resolution on the account of efficiency, in the present method the efficiency is enhanced by 10%, due to the enhanced surface emission of the converter. Further investigations are necessary in order to asses these effects. The present work revealed the technical difficulties of producing a good, durable converter and emphasizes the importance of the foil quality for a good detector performance.

5. ACKNOWLEDGEMENTS

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