Neutron-gamma survey system for decommissioning and dismantling activities

Jessica C. Delgado[1,2], Felix Pino[1], Erica Fanchini[3], Alessandro Iovane[3], Daniela Fabris[4] and Sandra Moretto*[1,4]

[1]Department of Physics and Astronomy "Galileo Galilei", University of Padova, Italy
[2]Department of Physics and Earth Science, University of Ferrara, Italy
[3]CAEN S.p.A., Viareggio, Italy
[3]INFN- Padova Section, Padova, Italy

(*) sandra.moretto@unipd.it

***Abstract*—The nuclear plant decommissioning and dismantling (D&D) operations will amount to €200 billion in costs over decades around the world, with three-fourths coming from Europe. Decommissioning includes activities such as planning, physical and radiological characterization, facility and site decontamination, dismantling, and materials management. This work is focused on the development of a compact, light and low-power consumption neutron-gamma survey system which could be easily mounted on an remotely operated vehicle. It is made up of a 4"x4"x2" NaIL (NaI:Tl + 1% ^{6}Li [95% enriched]) neutron/gamma scintillation detector coupled to a SiPM array. Digital pulse processing techniques were implemented to acquire and process the signals, by means of a CAEN DT5780 unit. A comprehensive characterization of this system, based on experiments and Monte Carlo simulations, is reported. The system can be used as a secondary inspection tool, useful for identifying radioactive and special nuclear materials in hotspots.**

***Keywords* — NaIL detector, D&D operations, radiation monitoring, neutron/gamma discrimination, hotspots.**

I. Introduction

THE decommissioning and dismantling (D&D) operations of nuclear facilities are crucial processes to safely retire and remove nuclear facilities (nuclear power plants, research reactors, etc.) from service. These operations involve a series of steps to ensure the safe management of radioactive materials, environmental protection, and the restoration of the site to a condition suitable for other uses. The D&D operations will cost an important amount of money and effort over decades around the world, in particular, in Europe will be more significant. As an example, in France, some thirty facilities are in the process of being dismantled or are pending to be dismantled. A determining part of the decommissioning includes the planning and preparation of physical and radiological characterization, which then, can facilitate the next steps of the operation: site decontamination, dismantling, materials management, etc. For that reason, the development of innovative systems to perform radiological surveys, taking advantage of the new technological advances in radiation detection, can save time, reduce costs, and minimize human intervention while increasing safety [1]. The development of techniques to characterize complex and/or poorly accessible structures, such as pipes, vessel internals, underground tanks with liquid radioactive waste, etc., are of particular interest currently [1]. Further development and use of robots, remotely operated vehicles, and drones equipped with radiation detectors could offer new options [2], especially in high-intensity radiation areas.

Different kind of sensors, such as gas filled, scintillation and solid state detectors have been used for radiation measurements (dose rate, gamma spectroscopy, estimation of activity, etc.) in the field of D&D of nuclear facilities. They have proven to be well developed and reliable. Very complex systems such as gamma cameras are currently employed to perform imaging in radiation monitoring applications, those can be based on semiconductor [3] or scintillation [4] detectors. Recently, the development of new scintillation materials, that offer excellent performance in terms of energy resolution [5], combined with the capability to detect thermal neutrons [6, 7], and taking advantage of the SiPM technology, has let to produce light, compact, and low power consumption systems [8], suitable to be deployed in D&D operations.

This work is focused on the preliminary study about the possibility to use a NaIL scintillation detector to perform neutron-gamma survey measurements. Specifically, the detector is made up of a 4"x4"x2" NaIL crystal coupled to a SiPM array. This detector offers thermal neutron counting and gamma-spectroscopic information. This system could be used as a secondary inspection tool of the site, mounted in a fixed position on an unmanned ground vehicle. It could be useful for characterizing and identifying the radioactive sources in hotspots located in large areas. Besides, thanks to the thermal neutron detection capability it could be used for recognition of special nuclear materials (such as: HEU, Pu, etc). Digital pulse processing of the detector signals is performed. The system has been extensively tested in laboratory conditions with point-like gamma sources, and neutron/gamma sources. A Monte Carlo simulation study, using GEANT4 v10.7 toolkit [9], is also reported. Specifically, the experimental gamma and thermal neutron responses of the detector are reported, including the high gamma background scenario. Besides, the absolute full-energy peak (@662keV) efficiency as a function of the angular position of the source has been studied. Finally, the energy resolution as a function of the interaction point of the gamma-ray in the NaIL crystal is reported.

II. Experimental details

A 4”x4”x2” NaIL (NaI:Tl + 1% ^{6}Li [95% enriched]) neutron/gamma scintillation detector coupled to a SiPM array purchased from Saint-Gobain Crystals company was used (see Fig. 1). The assembly detector includes an adapter board to simplify the power supply and data collection. A micro USB connector is used to provide the required +5VDC to the read-out board, and a coaxial MCX connector for the output signal.

A set of gamma-ray point-like calibration sources (with activities ~300 kBq) was employed: ^{137}Cs, ^{60}Co, ^{241}Am and ^{22}Na. Besides, neutron/gamma sources, ^{252}Cf and AmBe, with neutron emission rate of $2x10^{4}$ s^{-1} and $2x10^{5}$ s^{-1} respectively were used for the neutron measurements.

A CAEN DT5780 Digital Multi Channel Analyzer (100 MS/s, 14-bit, 16k Digital MCA) was used for the acquisition and processing of the NaIL pulses. The DT5780 unit features the DPP-PHA firmware, usually employed for gamma spectroscopy applications. Furthermore, a pile-up filter is included in the firmware, in order to obtain good results in situations of high counting rates. The unit is fully-controlled by CoMPASS Software.

Monte Carlo simulations of the gamma-ray and thermal neutron detection efficiencies of the NaIL detector were performed using the GEANT4 v10.7 toolkit. The *QGSP_BERT_HP* physics list was used, which contains high precision data for the transport of fast neutrons.

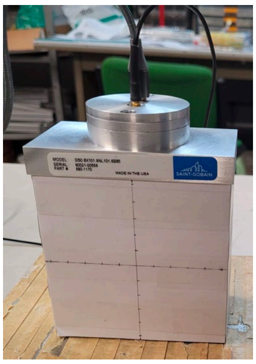

Fig. 1. Picture of the 4”x4”x2” NaIL detector

III. Results and discussion

A. Gamma-ray response

In Fig. 2a the energy spectra, corresponding to a ^{137}Cs source and a background, acquired with the NaIL detector are given. After the background subtraction, the energy resolution (% of FWHM) at 662keV obtained was 7.8%. Since the DPP-PHA firmware is based on the trapezoidal filter, the processing parameters were optimized in order to obtain the best results in terms of energy resolution. The optimal values are: rise time 3μs, flat top 1μs, pole zero 45 μs, peaking time 80%, and 4 samples of the flat top to get the amplitude of the trapezoid.

In Fig. 2b the energy calibration curve is presented. The explored energy range is 0.06-4.44 MeV. The best result was obtained by fitting the quadratic equation: $E[keV] = a\cdot Ch + b\cdot Ch^{2}$. As can be seen a small non linearity is exhibited by the detector. This behavior is commonly observed in large volume scintillators when a large energy range is taken into account.

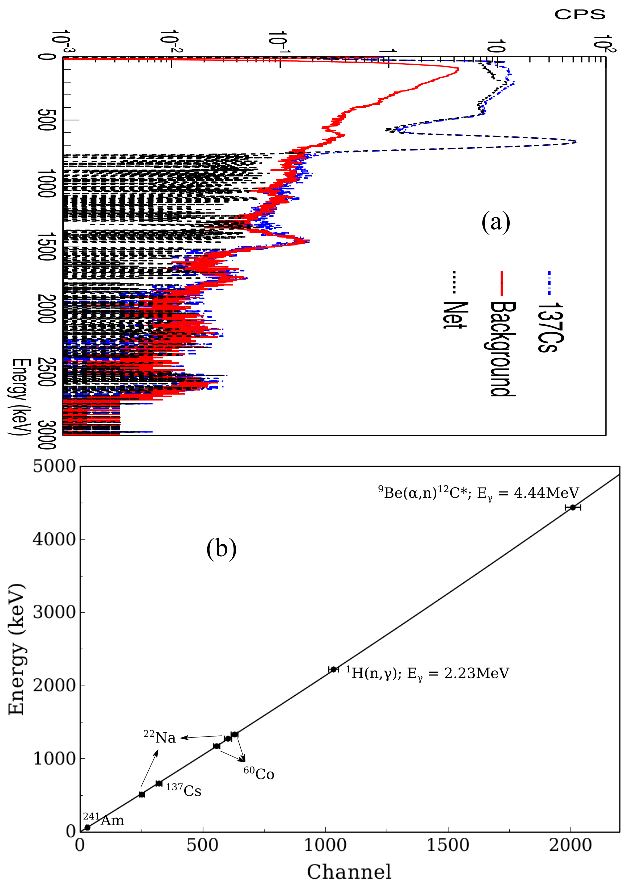

Fig. *2.* (a) ^{137}Cs spectrum acquired with the NaIL detector (FWHM[%] @662keV = 7.8 %). (b) Energy calibration curve of the NaIL detector. Fitted parameters are: a = 2.068, b = 7.127 x 10^{-5}.

B. Thermal neutron response

The NaIL detector responses corresponding to AmBe and ^{252}Cf neutron sources are shown in the Fig. 3. Each source was placed at 25 cm, and centered, from one of the larger faces of the detector. The fast neutrons emitted were moderated with 6cm of polyethylene. The associated “thermal neutron peak” is observed at 3.2 MeVee. Besides, in the case of the AmBe source, the 4.44 MeV peak, and the single escape (S.E.) peak can be also observed. It is important to mention that this structure can be used to identify neutron sources based on ^{9}Be(α,n)^{12}C reaction. As output, the read-out board provides a positive going charge sensitive tail-pulse with a 50 μs decay, so, pulse shape discrimination by performing pulse shape analysis of the output signal is not possible to execute. However, since the thermal neutron detection signature is observed at high energies (3.2 MeVee full-energy peak), for most of cases it is not necessary to perform neutron/gamma discrimination to get good results in terms of thermal neutron detection capability.

A Monte Carlo simulation of the intrinsic thermal neutron detection efficiency was performed using the GEANT4 v 10.7 toolkit. Thermal neutrons with energies of 0.025 eV were directed to one of the larger faces of the NaIL detector. The origin of the thermal neutrons was 25 cm away from the detector face. All the face was illuminated by the neutrons. The efficiency was estimated to be around 60%.

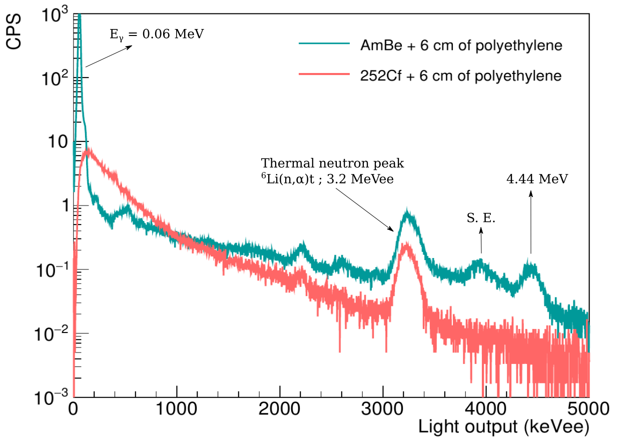

Fig. *3*. NaIL detector responses associated to AmBe and ^{252}Cf sources moderated with 6 cm of polyethylene.

C. Thermal neutron detection against the counting rate

The main reasons that can cause a loss of thermal neutron detection efficiency are the effects produced by a high counting rate, such as: pile-up events, dead time, summing events, etc., so, it is important to assess the response of the NaIL detector as a function of the measured counting rate.

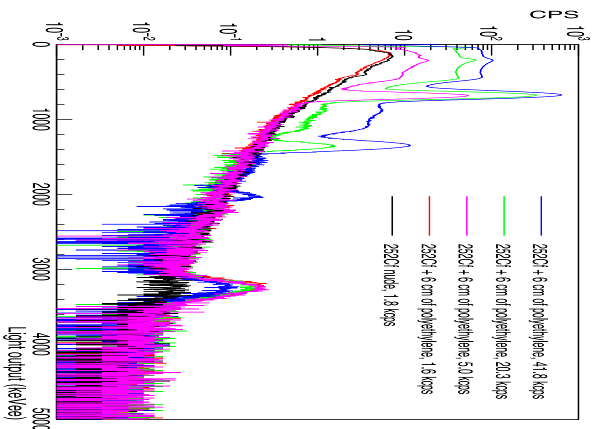

Fig. *4*. NaIL detector responses associated to different counting rates. ^{137}Cs source was used to modify the counting rate.

The measurements were performed using the ^{252}Cf moderated with 6 cm of polyethylene, combined with a ^{137}Cs source. The last one was used to increase the counting rate. In Fig. 4 several detector responses at different counting rates are shown. As can be seen the thermal neutron peak at 3.2 MeVee reduced its intensity as the counting rate increase (excluding the spectrum corresponding to the non-moderated ^{252}Cf source).

Fig. 5 shows the behavior of the thermal neutron detection efficiency as a function of the counting rate. Specifically, it is reduced by 50% when the measured counting rate of the system is around 40 kcps.

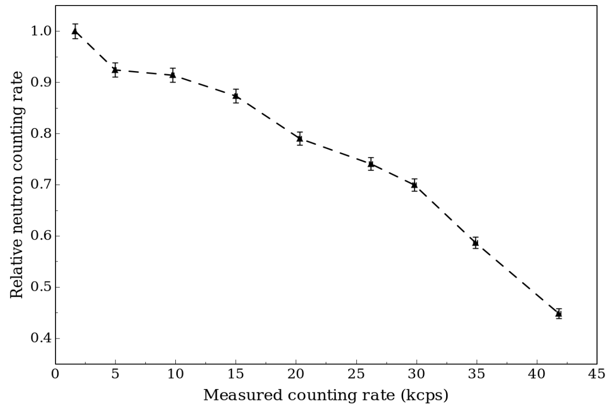

Fig. 5 Relative neutron counting rate against the measured counting rate.

D. Full-energy peak gamma efficiency vs angular position

In radiation monitoring applications, the response of the detector as a function of the position of the source with respect to the detector is an important scenario to be studied.

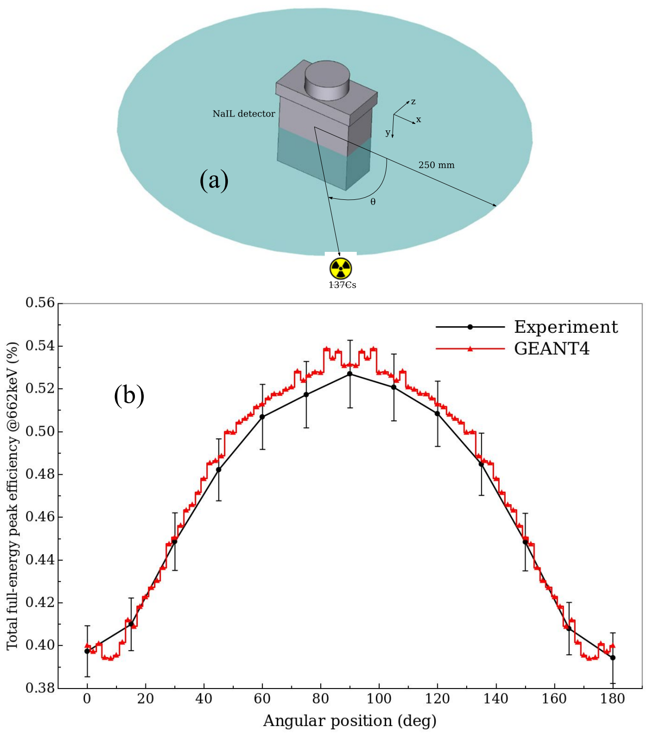

Fig. *6*. (a) Scheme of the measurement set-up. (b) Full energy peak efficiency @662keV of the NaIL detector as a function of the angular position of the source.

In this case, a ^{137}Cs source was placed at 25 cm from the center of the active volume of the detector (see Fig. 6a). The angular position of the source, θ, was changed in the range 0-180°. The absolute full-energy peak gamma efficiency at

662keV as a function of the angular position of the source is given in the Fig. 6b. Excellent agreement between the experimental and simulation results was obtained. The results suggest that at 1 meter, the minimum detectable activity (MDA) [10], of a ^{137}Cs source is between 3 and 4 kBq (taking into account a measurement time = 1 min), depending on the angular position of the source.

E. Energy resolution vs interaction point

The energy resolution at 662keV as a function of the initial interaction point of the gamma-ray was also studied. Figure 7a depicts a schematic representation of the setup. This setup involves the placement of a ^{137}Cs source within a collimator made of tungsten. The collimator is carefully positioned in front of both the smaller and larger faces of the detector, each separately. This arrangement is designed to examine how the energy resolution behaves in relation to the interaction point within the detector. A worsening behavior (up to 20% with respect to the best value) is observed as the interaction point becomes closer to the SiPM array, see Fig. 7b. In fact, the poorer energy resolution is observed when the initial interaction point is located in the smaller face and close to the height of the SiPM array. Taking into account that the mean free path of the 662keV photons in NaI is around 3.8 cm, it seems that an important amount of light is produced in the corners of the scintillator, making difficult its collection by the read-out device. No dependance is seen in the cross-line direction, at least at half height of the scintillator. In this configuration the best energy resolution is obtained, meaning that most of the scintillation light yield is efficiently collected.

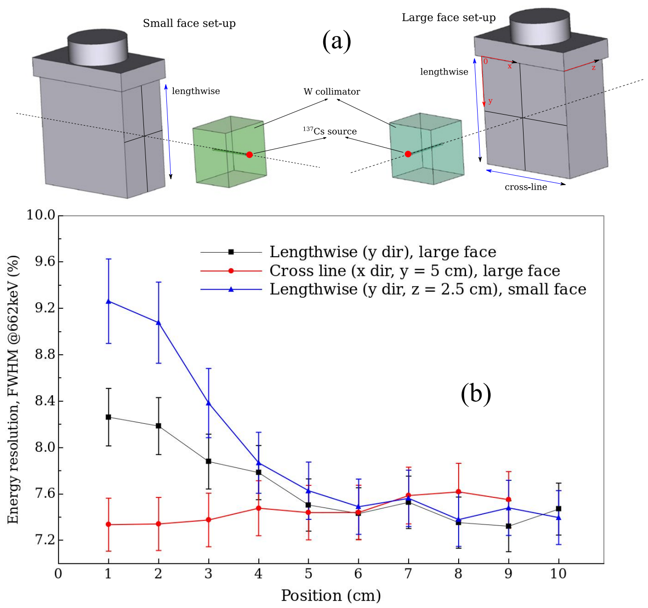

Fig. *7*. (a) Scheme of the measurement set-up. (b) Energy resolution (% of FWHM @662keV) associated at different interaction points.

IV. Conclusions

A comprehensive study of a large NaIL scintillator coupled to a SiPM array has been performed. It exhibits an energy resolution of 7.8% @662keV, and shows a slightly non-linear energy calibration when considering an energy range 0.06-4.44MeV. By Monte Carlo simulation the intrinsic thermal neutron efficiency was estimated to be 60%. The thermal neutron peak is clearly observed at 3.2 MeVee, and as the gamma background increase the thermal neutron detection efficiency decrease. Specifically, it is reduced 50% when the measured counting rate is about 40 kcps.

There is a strong dependance of the gamma detection efficiency as a function of the angular position of the source, and it has been well reproduced by the Monte Carlo model (difference lower than 5%). Taking into account the maximum value of gamma efficiency, the minimum detectable activity of ^{137}Cs was estimated to be 3 kBq (1 m away from the detector).

Finally, the energy resolution of the NaIL detector as a function of the initial interaction point was studied. In particular, a worse performance is observed when the interaction point is close to the SiPM array, meaning that in this situation it is hard to achieve a good collection of light.

According to the obtained results, we can conclude that a neutron-gamma survey system based on a high-efficient NaIL scintillation detector, that coupled to a SiPM array offers a compact, light and low-power-consumption solution, can fulfill the current requirements of the systems designed to perform the radiological characterizations in D&D operations. In the near future the integration of this system with a unmanned ground vehicle to perform a field test will be realized.

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