NEURAPID project

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INFN- LNF

1 Introduction

NEURAPID (CSN 5, 2014-2016) has the objective of developing instruments to measure neutrons in fields where the detection is made especially difficult due to the following aspects

- Very low fluence fields: fields with very low fluence rate such as the neutron component of the cosmic rays at ground level. Cosmic ray field at ground level is characterized by:
  - Continuous spectrum ranging from thermal up to GeV neutrons (12 orders of magnitude in energy)
  - Very low fluence rate, in the order of 10^{-2} cm^{-2} s^{-1} (integrated on the whole energy interval). Neutrons originated from the cosmic field and their variation with time are especially interesting for aircrew radiation protection and prevention of failures in electronic equipment of aircrafts.

- SPF (Single Pulse Fields): fields with pulsed structure, such as those produced in plasma-focus or ultra-intense laser based installations.

See website https://sites.google.com/site/csn5neurapid/ for more details

The work performed in 2014-2015 allowed reaching the following objectives:
- Setting up and characterizing metrology-grade thermal neutron facilities (ETHERNES @ LNF, HOTNES @ ENEA-Frascati, see Publications) for calibrating large area thermal neutron detectors in extended and very uniform thermal neutron field.
- Developing a spherical-moderator-based device (called SPEEDY) with isotropic response, for monitoring the neutron ambient radiation in pulsed fields.
- Developing a directional spectrometer (CYSP-HS, High Sensitivity), based on the CYSP geometry, for
  - Neutron measurements in very low intensity fields like the cosmic rays at ground level
  - Neutron measurements in single pulsed fields
- Developing and testing the thermal neutron detectors with large area (LATND) to be included in the mentioned devices. A LATND consists in a couple of 2.8 cm x 2.8 cm silicon diode coupled with a single thermal neutron radiator made of a 31 micron layer of ^{6}LiF. The device is developed at INFN-LNF starting from commercial semiconductors.

The 2016 activity was focused on testing SPEEDY and CYSP-HS in realistic fields.
The following realistic fields were chosen

2 The CYSP-HS device

In Figure 1 the structure of the CYSP-HS is shown. The overall diameter is 50 cm and total length 65 cm. The dimensions of the cylinder as well as the location of detectors have been chosen to maximize the “spectrometric capability” of the device, i.e. the degree of differentiation between the response functions associated to different detector positions. The collimator (label 1) is 30 cm in length and its collimating hole (label 2), 16 cm in diameter, is covered by 5 mm of borated plastic. The seven LATNDs, located along the cylindrical axis, are contained in a HDPE capsule (20 cm in diameter, 30 cm in length). An external shield made of 5 mm of borated rubber (label 3) plus 15 cm of HDPE (label 6) protects the sensitive capsule from lateral contributions over a broad energy range. A one cm thick, 20 cm in diameter, lead disk (label 4), has been inserted between 6th and 7th positions to increase the response to high-energy neutrons. The distance between two adjacent detector cavities is 2 cm (centre to centre). The seven detectors are located at depths 4, 6, 8, 10, 12, 14 and 21 cm from the end of the collimator. The latter is located under the one-cm lead filter. Label 5 symbolizes eight cylindrical air cavities, one cm in diameter, designed to enhance neutron streaming towards the deeper detectors.

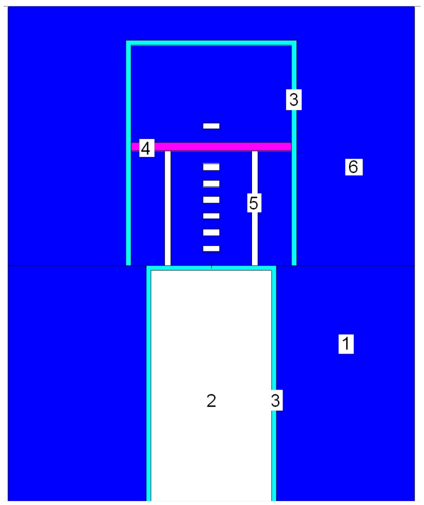

Figure 1: CYSP-Hs structure.

The response matrix of the CYSP-HS is defined as the number of counts in every LATND per unit neutron fluence, as a function of the neutron energy, when the device is uniformly irradiated along the collimation direction. This matrix was derived with MCNPX (See Figure 2) and its values depends on:
- the detector position (from 1, the shallowest, to 7, the deepest)
- the neutron energy (energies from thermal domain up to GeV were investigated).

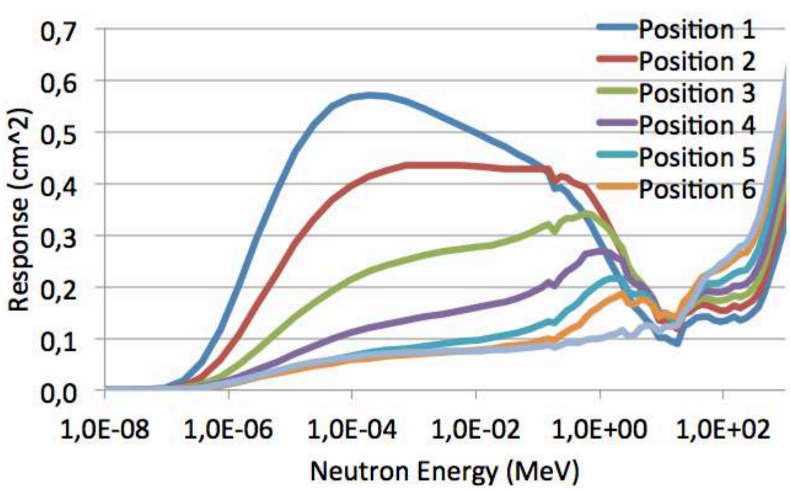

Figure 2: CYSP-HS response matrix (counts per unit fluence as a function of energy and detector position).

The simulated response matrix was experimentally evaluated by exposing the device in a reference ^{241}Am-Be neutron field available at the Politecnico di Milano metrology labs (fluence rate at measurement position 10.4 $cm^{-2}s^{-1}$ ± 1.3%). In Fig. 3, the observed and expected count rates in the different detector positions are compared. This allowed estimating the overall uncertainty of the CYSP-HS response matrix as ±3% (in the 0.1 - 10 MeV energy region, covered by the Am-Be spectrum).

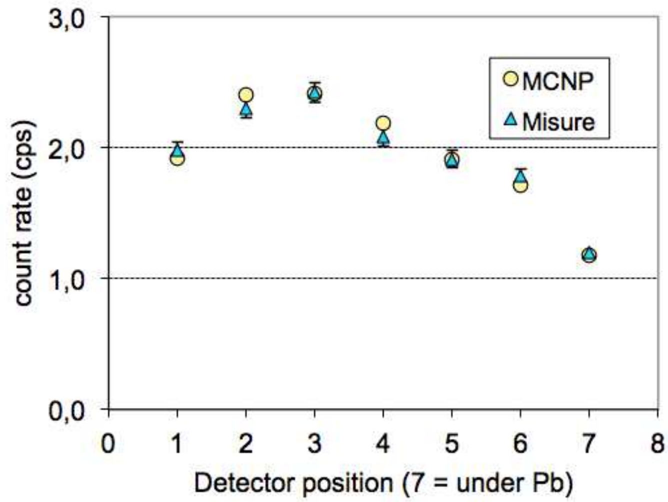

Figure 3: Observed and expected count rates in the CYSP-HS detectors, when the device is exposed in a reference ^{241}Am-Be neutron field (Politecnico di Milano).

3 CYSP-HS: Tests in cosmic neutron field

Under collaboration with Helmholtz Zentrum Munchen, HMGU The device CYSP-HS was installed in March 2016 on the Environmental Research Station (UFS) 'Schneefernerhaus' located some 300 m below the Zugspitze summit, corresponding to 2650 m above the sea level, in Germany (See Fig. 4).

Figure 4: The environmental Research Station (UFS) Schneefernerhaus, Zugspitze mountain, 2650 m a.s.l.

The CYSP-HS was oriented in the vertical direction, with the purpose of measuring only the top-to-down component of the cosmic neutron field. The seven detectors of CYSP-HS are connected to a multi-detector analogue board, designed within the NEURAPID activities, formed by up to eight parallel pulse elaboration chains. Every analogy chain consists of a charge sensitive preamplifier (type CREMAT CR110) followed by a shaper amplifier (type CREMAT CR200 with variable shaping time from 100 ns up to 8 microseconds). For the cosmic measurements, a shaping time of 2 microseconds was selected.
The output of the analogue board is processed by an 8 channel commercial digitizer (up to 2 MS/s per channel). The pulses are thus detected, and classified in height distributions (spectra). The digital data are collected by a LabView program. The whole system is remotely controlled via Teamviewer.
As an example, the pulse height spectrum from LATND in position 7 is shown in Fig. 5. The contribution of the photons to the spectrum was inferred according to the data from a LATND exposed without 6LiF

converter ("bare" detector). The neutron contribution ("net" spectrum) is obtained by subtracting the photon spectrum from the total spectrum. The counts due to thermal neutron reactions in the 6LiF converter are calculated as the sum of the net spectrum from pulse height about 0.6 V to 1.5 V. This quantity was derived for every detector position in the CYSP-HS and used for the unfolding procedure, performed using the FRUIT unfolding code developed within the group (Bedogni et al., Nucl. Instr. and Meth. A 580 (2007) 1301).
The typical cosmic neutron spectrum obtained by unfolding the CYSP-HS data is reported in Fig. 6. Total neutron fluence rates are in the order of 1E-2 $cm^{-2}s^{-1}$.
Spectra from CYSP-HS are currently under comparison with those obtained, in the same environment, with the Extended Range Bonner Sphere Spectrometer (ERBSS) from HMGU Munich.
A remarkable advantage of CYSP-HS with respect to ERBSS is its insensitivity to components that differ from the collimating one, i.e. the vertical one in this case. Differently, the ERBSS sees all directional components with the same weight, including the albedo (scattering from the ground and the surrounding materials - snow, in particular). CYSP-HS capability of directly monitoring the vertical cosmic neutron component may significantly contribute in the activities of:
- benchmarking the computational codes used by airlines for aircrew dosimetry;
- Promptly detecting cosmic rays anomalies able to produce significant increases in the neutron doses at flight altitudes.

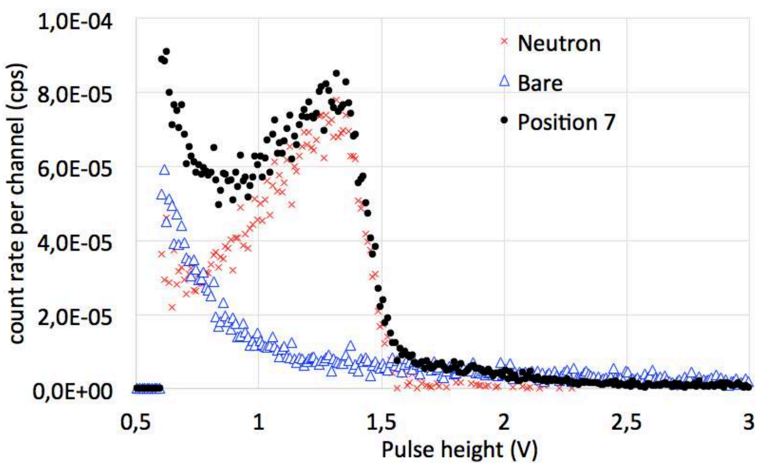

Figure 5: Typical pulse height spectrum of the LATND located in position 7. The photon signal is obtained from the "bare" detector data. The "neutron" spectrum is the difference between the total and the photon spectra.

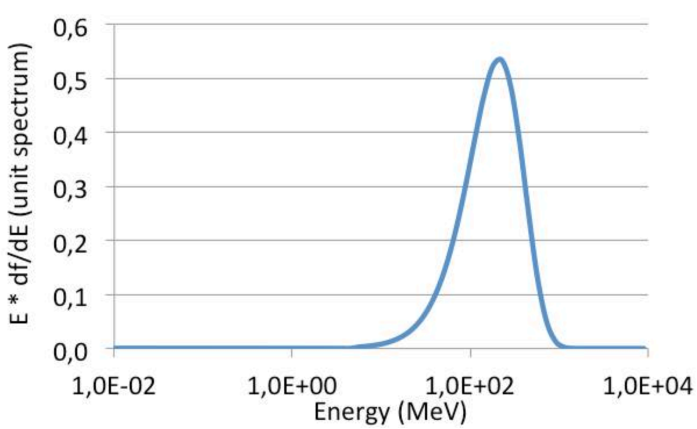

Figure 6: Typical cosmic neutron spectrum obtained by unfolding the CYSP-HS data. The spectrum is normalized to unit fluence and in equi-lethargy representation.

4 CYSP-HS: Tests in pulsed fields

CYSP-HS was tested in the pulsed neutron fields produced at SARAF facility (SOREQ Nuclear centre, Israel), where intense neutron fields from hundreds keV up to 2.5 MeV (maximum energy) are achieved by bombarding thin (solid) or thick (liquid) Lithium targets with protons from 2.1 MeV to 4 MeV. The proton current can be varied, according to the target type, from few hundred nA up to 2 mA. The beam time structure can be varied from continuous CW beam up to few Hz.

The device was exposed with a fixed set-up (500 microA peak current, 1920 MeV protons on Liquid Lithium target), but varying the time structure:

- pulse duration 0.1 ms, 10-50-100-500 Hz;
- pulse duration 1 ms, 10-50-100-500 Hz;
- pulse duration10 ms, 10-50-100 Hz;
- pulse duration 0.01 ms, 500 Hz,
- Continuous.

The instrument reference point (front face centre) was placed at about 202 cm in the forward direction from the Liquid Lithium target centre. The neutron spectrum obtained by unfolding the experimental ("continuous" time structure) data with the FRUIT code is shown in Fig. 7.

The total neutron fluence at the CYSP-HS reference point is (6207±190) $cm^{-2}s^{-1}$. By varying the time structure according as described above and repeating the unfolding, the variability of the total fluence divided by the duty cycle (pulse duration x repetition rate) is < 2%, indicating a satisfactory linearity and capability of working with a large variety of pulsed structures. In all cases the numerical spectra are comparable within the uncertainties indicated in Fig. 7.

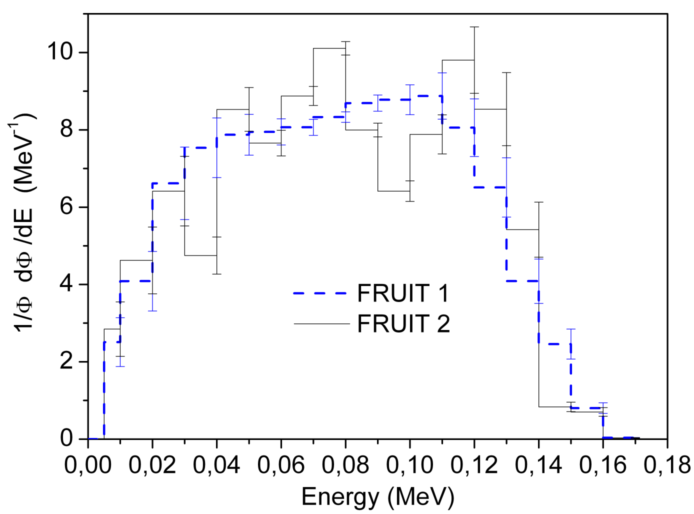

Figure 7: Neutron spectrum obtained by unfolding the CYSP-HS data with FRUIT. FRUIT 1 and FRUIT 2 refer to different "guess spectra" used to start the unfolding process.

5 The SPEEDY device

The SPEEDY detector is a 22 cm diameter spherical device with an internal cavity (4 cm height x 4 cm diameter) to allocate a LATND, see Figure 8.

The central LATND is connected to the NEURAPID analogue board. Here the pulse processing is operated through a CREMAT CR-111 charge preamplifier followed by a 250 ns CR-200 shaper amplifier. The output of the analogue board is processed by an 8 channel commercial digitizer (up to 2 MS/s per channel). The pulses are thus detected, and classified in height distributions (spectra). The digital data are collected by a LabView program. The counts due to thermal neutron reactions in the 6LiF converter are calculated as the sum of the pulse height spectrum in a defined ROI (from pulse height 0.6 V to 1.5 V).

The SPEEDY response function in terms of ambient dose equivalent H*(10) is defined as the expected number of counts in the LATND per unit H*(10), as a function of the energy, when the device is uniformly irradiated. This is shown is shown in Fig. 9 (data from MCNPX simulation and experiment with mono-energetic neutrons, see below).

Figure 8: The SPEEDY detector, made of a 22 cm diameter sphere, and the detector cylindrical insert (detector cavity: 4 cm height x 4 cm diameter).

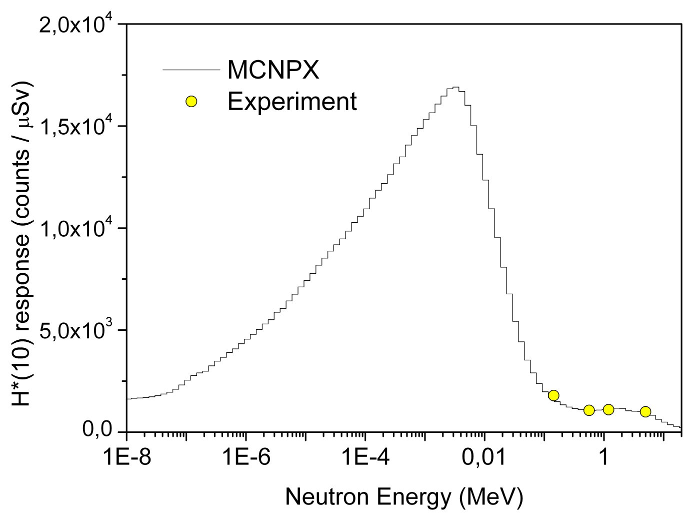

Figure 9: SPEEDY Response function in terms of ambient dose equivalent H*(10): simulated values (curve) compared with experiment with mono-energetic neutrons at few neutron energies.

The following tests have been performed with the SPEEDY device:

- Calibration with mono-energetic neutron beams at NPL (UK) primary metrology lab. Neutron energies: 0.144 MeV, 0.565 MeV, 1.2 MeV, 5 MeV. As demonstrated in Fig. 9, the experiment fully confirmed the expected response function.
- Measurement in the pulsed field produced at n@BTF neutron facility at INFN-LNF (done in 2015). The SPEEDY was irradiated in the n@BTF pulsed fast neutron beam at 130 cm from the neutron emitting target, in the 90° direction from the incident 510 MeV electron beam. Beam time structure was 10 ns pulse duration, 2 Hz, about 2E+8 electrons/pulse. The detector was exposed to a neutron fluence of about 130 cm^{-2} per pulse. The instrument proved capability to correctly distinguish different the pulses with no appreciable pile-up.

6 Publications

- Bedogni, R., Sperduti, A., Pietropaolo, A., Pillon, M., Pola, A., Gomez-Ros, J.M. Experimental characterization of HOTNES: A new thermal neutron facility with large homogeneity area. NIM A (2016). DOI 10.1016/j.nima.2016.10.056

- Irazola, L., Terron, J.A., Bedogni, R., Lorenzoli, M., Sanchez-Nieto, B., Gomez, F., Sanchez-Doblado, F. Improving the neutron-to-photon discrimination capability of detectors used for neutron dosimetry in high energy photon beam radiotherapy. Applied Radiat. Isotopes 115 (2016) 49-54.

- Bedogni, R., Sacco, D., Gomez-Ros, J. M., Lorenzoli, M., Gentile, A., Buonomo, B., Pola, A., Introini, M. V., Bortot, D., Domingo, C. ETHERNES: A new design of radionuclide source-based thermal neutron facility with large homogeneity area. Applied Radiat. Isotopes 107 (2016) 171-176.

- Irazola, L., Praena, J., Fernandez, B., Macias, M, Bedogni, R., Terron, J. A. Sanchez-Nieto, B. Arias de Saavedra, F. Porras, I. Sanchez-Doblado, F. Using a Tandem Pelletron accelerator to produce a thermal neutron beam for detector testing purposes. Applied Radiat. Isotopes 107 (2016) 330-334.