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Article

The Effect of Decreasing Aperture Diameter on Signal Transmission from the Scintillator to the Photomultiplier Tube Over a Wide Energy Range

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Abstract: In this paper, we study the effect of decreasing aperture diameter on signal transmission from the scintillator to the PMT. The apertures have been inserted directly between the scintillator and the photomultiplier. Three different aperture diameters have been used over a wide energy range. A newly developed fast digital spectrometer has been utilised for experimental measurement in the radial channel of the VR-1 research reactor. The detector signals with and without inserted apertures have been measured and evaluated. The aim of our research was to determine the effect of the apertures on the spectral quality, energy range and the evaluated physical quantities.

Keywords: digital analyser; scintillator; photomultiplier tube (PMT); pulse shape discrimination (PSD); gamma spectrometry; monte Carlo (MC); VR-1 research reactor

1. Introduction

This paper can be considered as an introductory study on the development of radiation detectors based on semiconductor diodes or optical fibers. In the development of these detectors, we work with a smaller detection area, i.e. a lower light output signal than conventional detectors consists with a scintillator and PMT.

In order to assess the effect of decreasing aperture diameter on spectral quality, energy range, and evaluated physical quantities, we provided a series of measurements with apertures of different diameters inserted between the scintillator and PMT. Our experimental arrangement of the scintillator and PMT eliminates the effect of using different types and sizes of semiconductor diodes and optical fibers.

The radial channel of research reactor VR-1 installed in Czech Technical University Prague has been used for the experimental measurements. The input analog signal from the detector has been digitized with a fast 12-bit analog to digital converter with a sampling frequency of 1 GHz. Digital signal processing is implemented into FPGA. Measured data from the detector have been processed into gamma spectra. The results of the development and experimental measurements are presented.

2. Instruments and Methods

The cylindrical stilbene organic scintillator of (45 x 45) mm with PSD properties has been used for the measurements. The Hamamatsu photomultiplier type R329-02 has been connected with a newly developed high voltage divider with negative voltage power. The active divider has a better ability to compensate for non-linearity caused by high pulse frequency and amplitude. The analog signal from the detector has been connected to a digital spectrometer.

The digital spectrometer is built as a modular system allowing the use of different types of scintillation detectors. The preamplifier splits the signal from the detector into two branches. Each branch is differently amplified and digitized by separate ADC. Different amplification increases the dynamic range of particles that the spectrometer is able to process.

The input analog signal is digitized with fast 12-bit analog to digital converter with a sampling frequency of 1 GHz. Digital signal processing is implemented into FPGA. FPGA is able to process all data flowing from ADC (12 Gbits per second). The spectrometer is connected with a computer via an optical ethernet of 10 Gbit (see Figure 1).

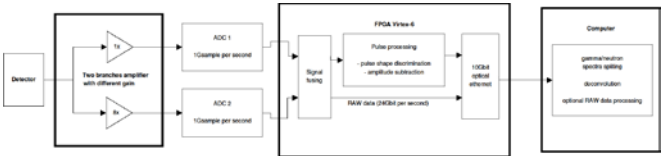


Figure 1. Scheme of the digital analyser.

2.1. Energy Calibration

Integrated digitized pulses have been linearly calibrated in keVee units, or keV electron equivalent. The linear transformation coefficients were derived from positions of the Compton edges [1] in the spectra of two gamma-ray sources ¹³⁷Cs and ⁶⁰Co. Sources of activity 350 kBq have been placed on the center of the front face detector. Measurement time has been determined in accordance with count rates from the detectors. A negative high voltage of 1 150 V has been adjusted.

2.2. Experimental Setup

The VR-1 research reactor is a light-water, zero-power pool-type reactor installed in the laboratories of Czech Technical University in Prague. The core consists of tubular fuel assemblies of IRT-4 M type enriched to 19.75 wt. % of ²³⁵U and can contain several dry vertical channels with different diameters up to 90 mm intended for experimental measurements. Fuel assemblies are formed by combinations of 4 to 8 concentric tubes according to the fuel element type. Fissile material in each fuel tube has a form of uranium dioxide dispersion in aluminium and is clad by aluminium alloy from both sides.

Up to two horizontal channels, tangential and radial, can be utilized for extracting larger neutron beam out of the core. The measurements have been carried out in the radial channel of the VR-1 research reactor with the C16 core, which layout is displayed in Figure 2. The speciality of the C16 core is the installation of three pieces of assemblies with stainless steel pins (see Figure 2, positions D7, E7, and F7) placed in the opposite direction to the radial channel.

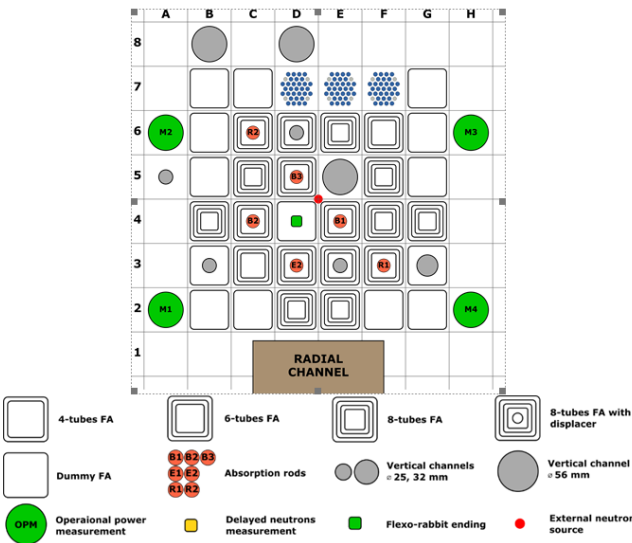


Figure 2. Layout of C16 core of the research reactor VR-1.

The experimental arrangement in the reactor hall is shown in Figures 3 and 4. The radial channel's inner diameter is 251 mm and the total length of the channel is 1 925 mm. Measurements have been carried out in the centred position of 1 400 mm from the front end of the channel. The nuclear reactions in the core of the reactor produced characteristic gamma lines with energies from 7 to 9 MeV.

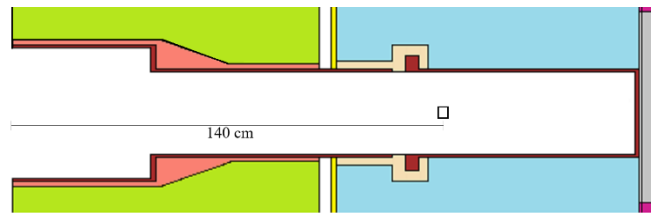


Figure 3. Detector arrangement in the radial channel of the VR-1 experimental reactor.

Three apertures made of matt steel have been used for the measurement. The outer diameter of the apertures is 53 mm and thickness 0.1 mm. The inner diameters of the apertures are 5, 12 and 25 mm and hole are filled with air. The apertures have been inserted directly in contact geometry between the radiation detector and the PMT.

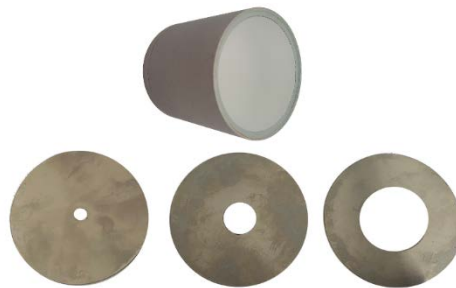


Figure 4. Stilbene detector and apertures used for the measurement in radial channel of the VR-1 experimental reactor.

2.1. MCNP Calculations

The flux density in the radial channel as well as the detector light output response have been calculated in the Monte-Carlo MCNP6.2 code using ENDF/B-VII.0 nuclear data libraries. The gamma spectrum in the radial channel has been calculated in the critical mode of calculation including neutron and photon transport. 2 million neutrons have been preset for the calculations in one generation and more than 20.000 active generations were simulated. The result is acceptable statistics in energy lines appearing between 7 and 10 MeV.

3. Results and Discussion

We carried out a measurement of the gamma spectrum in the radial channel of nuclear reactor VR-1. Three different diameters of apertures have been used in experimental measurements in energy range from 1 to 7 MeV, see Figure 5.

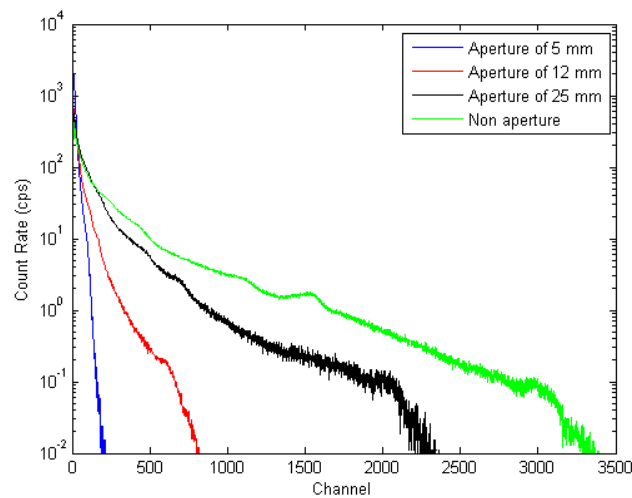


Figure 5. Apparatus gamma spectra with various apertures.

The analyser stores the measured data in a form of a pulse shape discrimination matrix, which preserves the information about the energy of the particle and particle type. This matrix can be downloaded into a PC for further processing. The apparatus spectra have been unfolded into the energy spectrum using calibration information and detector response function. The pulse-shape discrimination capabilities of the stilbene detector have been evaluated and the results are presented in Figure 6.

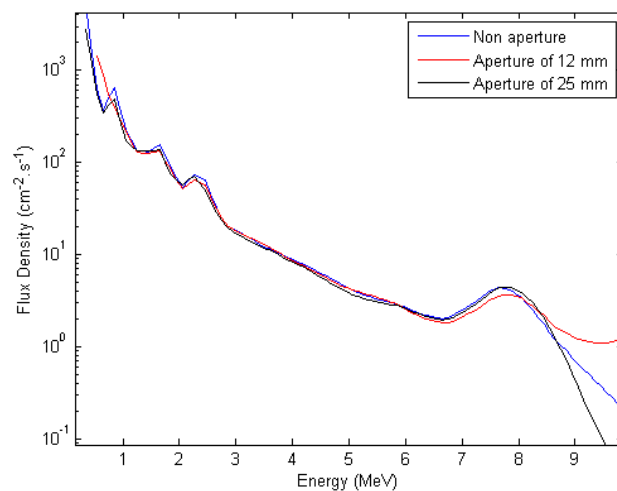


Figure 6. Gamma spectrum in the radial channel of experimental reactor VR-1.

The MC simulations of the light output response matrix of the stilbene detector have been performed using MCNP code 6.2. A MC model was set up to calculate the absolute energy response to photons. Figure 7 shows the calculated light output response of stilbene detector as a function of photon energy.

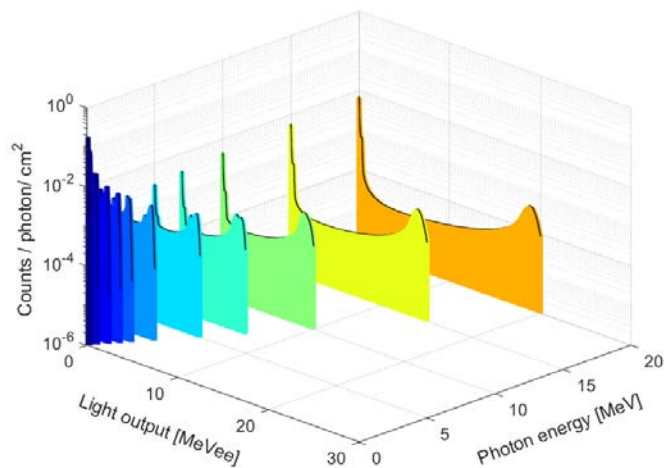


Figure 7. The stilbene detector light output response for gamma radiation.

4. Conclusion

In this paper, effect of decreasing aperture diameter on signal transmission from the scintillator to the photomultiplier has been performed. A wide gamma energy range was ensured by using experimental reactor VR-1.

We compared evaluated gamma spectra, see Figure 8 with published spectra [2] and simulated spectra. The flux density in the range of low energies is higher than the published spectra. The reason is a high level of fission products namely ^{140}La , ^{95}Zr and ^{95}Nb . The ^{95}Zr and ^{95}Nb peaks are also observed in previously measured spectra. The amplitude of this peaks is lower due to long decay time.

Simulated gamma flux density, see Figure 8, in the radial channel of reactor VR-1 corresponds with a measurement provided during a Mock-Up experiment for the benchmarking of high power reactors [3,4].

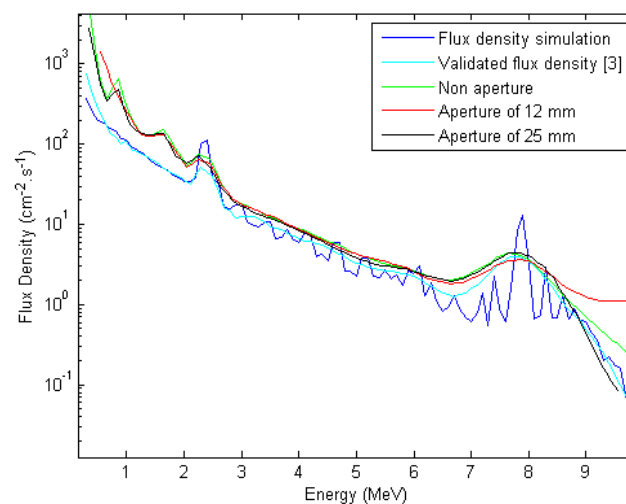


Figure 8. Comparison of gamma spectra in the radial channel of reactor VR-1.

The energy of the particle detected by the stilbene detector corresponds to a certain level of the output voltage pulse. If we insert an aperture between the PMT and the detector, due to the lower light intensity detected by the PMT, the level of the output voltage pulse will decrease and the

spectrum will shift towards the lower channels (see Figure 4). Shading the effective area between the scintillator and the PMT by 50 % shortens the spectrum by about 1 000 channels compared to the total unshielded effective area. In the case of 75 % shading, we observe a shortening of the spectrum by about 2 500 channels. In both cases, it is still possible to perform the unfolding of the apparatus spectrum, see Figure 6. At 90 % shading, the spectrum shortens by 3 200 channels and steeply decreasing, see Figure 5. No Compton edges are identified in the spectrum and such an apparatus spectrum can no longer be evaluated. Aperture diameters of 12 and 25 mm correspond to commonly available semiconductor diodes or optical fibre bundles. Due to their small diameter, a similar spectral shortening effect can be expected with respect to their near quantum efficiency.

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