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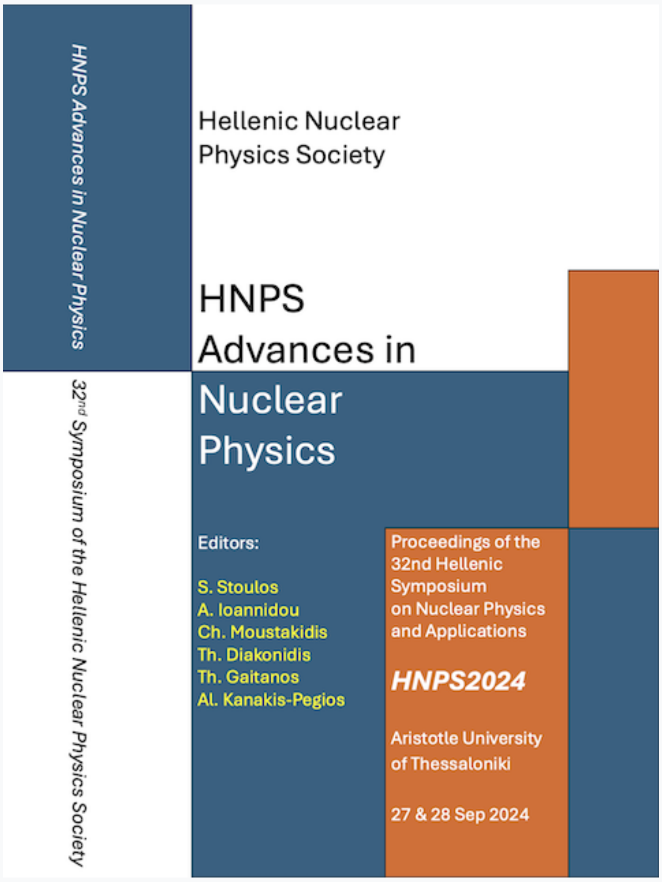

Neutron capture reactions for nuclear astrophysics: Development & characterization of an innovative detection setup based on trans-Stilbene organic scintillators

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Neutron capture reactions for nuclear astrophysics: Development & characterization of an innovative detection setup based on trans-Stilbene organic scintillators

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Abstract Neutron capture reactions are essential for understanding stellar nucleosynthesis beyond iron and the formation of elements in the universe. This study presents the development and characterization of a novel detection setup utilizing trans-Stilbene organic scintillators, developed at DFA (Dipartimento di Fisica e Astronomia "Ettore Majorana", Catania) and INFN-CT, to enhance neutron capture measurements for nuclear astrophysics.

A fully symmetrical multi-detector array was created, arranging the trans-Stilbene modules in a regular tetrahedral configuration to optimize geometric efficiency. The detectors were evaluated under various operation modes (pulse height/charge) and tested for neutron/gamma discrimination using Pulse Shape Discrimination (PSD). Additionally, a multivariate approach employing Principal Component Analysis (PCA) was implemented to handle multiple pulse characteristic parameters effectively.

The results highlight the potential of trans-Stilbene detectors to replace traditional C_6D_6 detectors at n_TOF/CERN, offering improved performance. The study also underscores their promising applications in both elastic and inelastic neutron scattering reactions, reinforcing their versatility and enhanced suitability for nuclear astrophysics research.

Keywords Neutron capture reactions, Nuclear Astrophysics, Detector characterization, Pulse Shape Discrimination (PSD), Principal Component Analysis (PCA)

INTRODUCTION

The motivation for this research stems from the need to improve neutron capture measurements, which are essential for understanding the processes of stellar nucleosynthesis. Traditional detectors, like C_6D_6, face challenges related to toxicity and flammability, prompting the exploration of safer and more efficient alternatives. Trans-Stilbene organic scintillators from both INRAD [1] and PROTEUS [2] offer excellent n/γ discrimination, good timing performance and they are non-toxic, making them ideal candidates for this application. By developing and characterizing a new detection setup based on these scintillators, this work aims to provide a robust and innovative solution for high-precision neutron capture studies in nuclear astrophysics, particularly aimed at (n,γ) experiments at the n_TOF facility at CERN.

To address challenges deriving from the use of the high neutron flux at the n_TOF facility at CERN [3-5], small-volume segmented total-energy detectors (sTED) [6] were implemented, offering better signal over background performances. Meanwhile, the hazardous nature of C_6D_6 liquid scintillation detectors has driven the proposal of trans-Stilbene organic scintillators, which are safer, solid, and have a higher density, providing a fast light response (~20 ns pulse width) [7-10].

The solid-state nature of Stilbene eliminates the need for quartz-crystal windows, reducing neutron sensitivity. Moreover, the eventual adoption of Silicon Photomultipliers (SiPMs) could provide a more compact and efficient alternative to bulky Photomultiplier Tubes (PMTs) while enabling lower-voltage operation. Our efforts focused on fully characterizing Stilbene crystals, specifically INRAD and

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PROTEUS, and integrating them into multi-detector arrays as high-performance alternatives to traditional C_6D_6 detectors, addressing both safety and efficiency concerns. Advances in time-of-flight (TOF) technique, for measuring neutron capture cross sections across a wide energy range, have significantly improved energy determination, crucial for n-capture experiments devoted to the determination of s-process abundances in peculiar stellar conditions [11,12]. These developments, along with the adoption of small-volume organic scintillators, have enhanced the precision of neutron capture measurements, marking substantial progress in neutron capture research at the n_TOF facility.

EXPERIMENTAL DETAILS & RESULTS

This research is focused on the development and characterization of trans-Stilbene crystals for neutron detection. Four solid, lightweight, non-hygroscopic, and non-flammable Ø1”×1” crystals (three INRAD and one PROTEUS), produced using proprietary growth techniques, were assembled into detector modules at INFN-CT and tested for their performance. The modules are housed in cylindrical carbon fiber casings, with a 50 μm Aluminum front window and coupled with a R7378A–Hamamatsu PMT (Photomultiplier Tube), connected to a PS1807-Sens-Tech active base with a DC-DC converter [13]. This ultra compact power base was tested as a low-voltage high-counting rate device. The detectors were characterized using rise/fall time measurements, pulse-height and charge spectra, and energy calibration, with data collected through a CAEN 8 Channel 12 bit 3.2 GS/s Switched Capacitor Digitizer. Both crystal types showed comparable performance, and the significance of digitization in neutron detection was emphasized, by fully exploiting the information contained in the digitized signal waveform. A schematic of the modules is reported on Fig. 1.

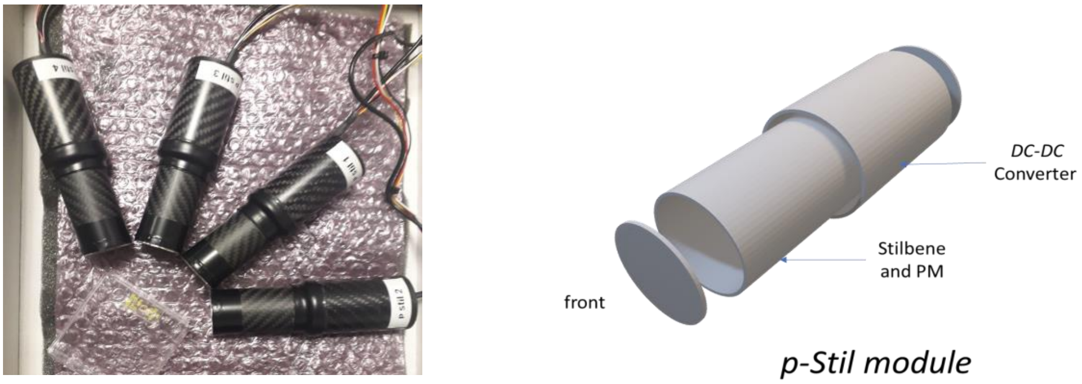

Figure 1. *A picture of the four trans-stilbene modules, labeled as “p-Stil #” (left). A schematic of the module (right).*

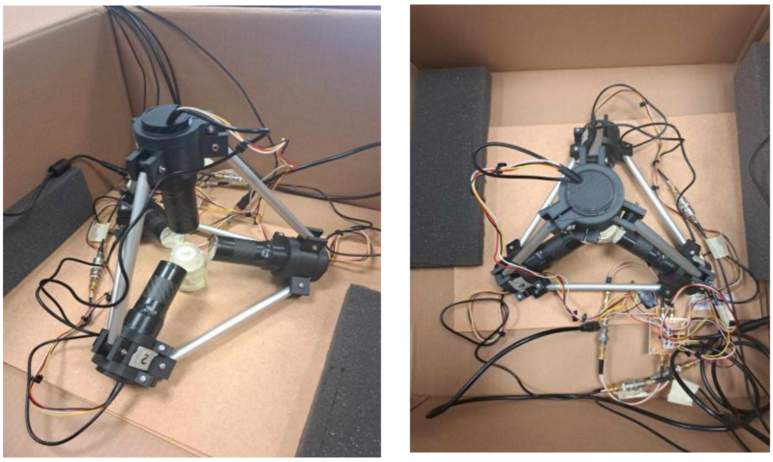

Figure 2: *A picture of the multi-detector array. Side view (left). Top-down view (right)*

An innovative multi-detector array, arranged in a tetrahedral configuration (Fig. 2), was developed using four trans-Stilbene detectors. The good time resolution and the PSD capabilities of the detector array make it highly effective for neutron and gamma detection. Additionally, the array holds potential for applications in space environments, such as solar neutron flux characterization and real-time optimization of detection efficiency.

In this context, complementary GEANT4 simulations validated the detector's efficiency for gamma and neutron interactions, offering proof-of-concept for future implementations.

Neutron & Gamma Efficiency curves

GEANT4 simulations were used to evaluate the detector's performance, with a focus on determining the efficiency of gamma and neutron detection, with a 50 keV deposited energy detection threshold, at various energies to enhance detection capabilities and tune future implementations.

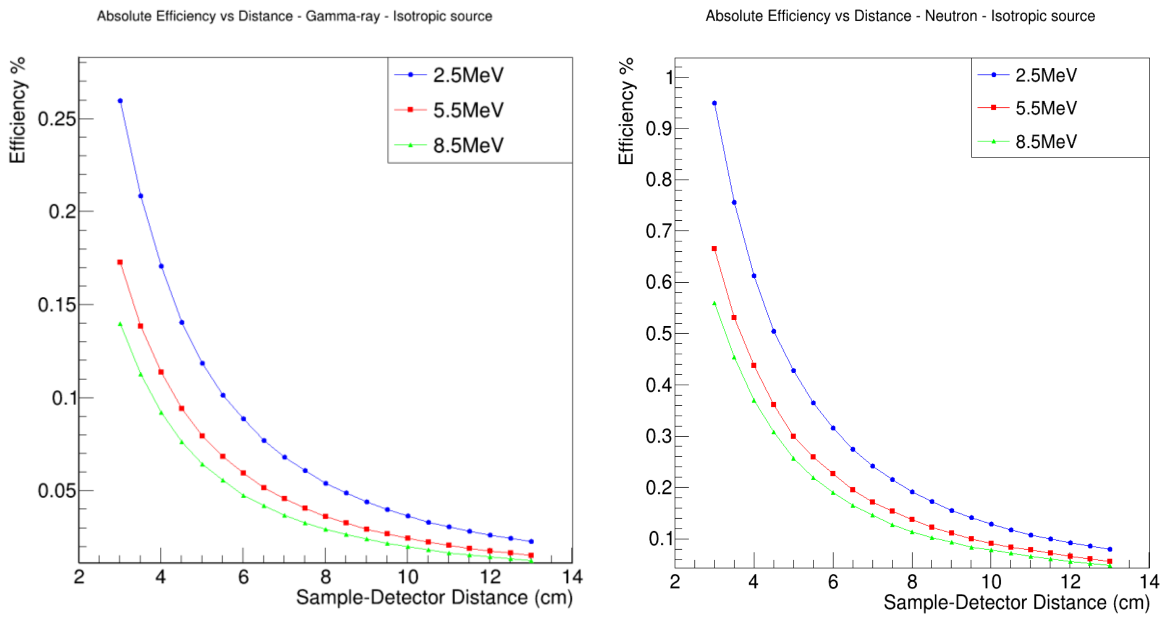

Figure 3. *Simulated absolute efficiency curves vs distance for different energy values. Gamma-rays (left). Neutrons (right)*

Rise & Fall Time measurements

Rise and fall times are key metrics in radiation detectors. The measurements were conducted by exposing the array to ^{137}Cs and ^{60}Co sources. To improve accuracy in low signal-to-noise conditions, a Savitzky-Golay filter was applied, smoothing the signal waveforms and thus improving interpolation and extrapolation. After filtering and analyzing around 40'000 events, the rise and fall times for INRAD and PROTEUS crystals were found to be nearly identical, confirming consistent performance between the two crystal types (Table 1).

Table 1. *Rise/Fall time measurements for INRAD and PROTEUS crystals (10%-90% & 90%-10%).*

	Rise Time (ns)	**Fall Time (ns)**
INRAD	3.966 ± 0.003	14.13 ± 0.06
PROTEUS	4.051 ± 0.002	14.43 ± 0.05

γ-γ Time Coincidence measurements

Accurate timing is essential for radiation detectors involved in TOF measurements, and it depends on both detector properties and the processing electronics. Time pick-off inaccuracies, such as time jitter and amplitude walk, are common, especially when dealing with signals of varying amplitudes. Leading edge timing is a simple method that works well with a narrow dynamic range but is prone to inaccuracies when the range broadens. Crossover timing, using bipolar pulses, reduces amplitude walk but introduces, in some cases, time jitter. In this study, three methodologies were implemented to determine time resolution: Leading Edge, a software-implemented Constant Fraction Discriminator (CFD), and zero-crossing determination after applying a software derivative, to evaluate time resolution. The results, gathered using the multi-detector array and a ^{60}Co source, placed at the centroid of the tetrahedral setup, showed that both INRAD-INRAD and PROTEUS-INRAD pairs had similar timing performance, with the second demonstrating slightly better resolution across all timing methods (Table 2). A -10mV trigger threshold was used for the leading-edge timing.

Table 2. *Time Resolution calculations for INRAD - INRAD and INRAD - PROTEUS detector pairs, using the three timing methodologies mentioned in the text above.*

	Time Resolution (ns)	
	INRAD - PROTEUS	**INRAD - INRAD**
Derivative	0.74 ± 0.03	1.08 ± 0.02
Leading Edge	0.78 ± 0.03	1.12 ± 0.02
CFD	0.73 ± 0.03	1.13 ± 0.03

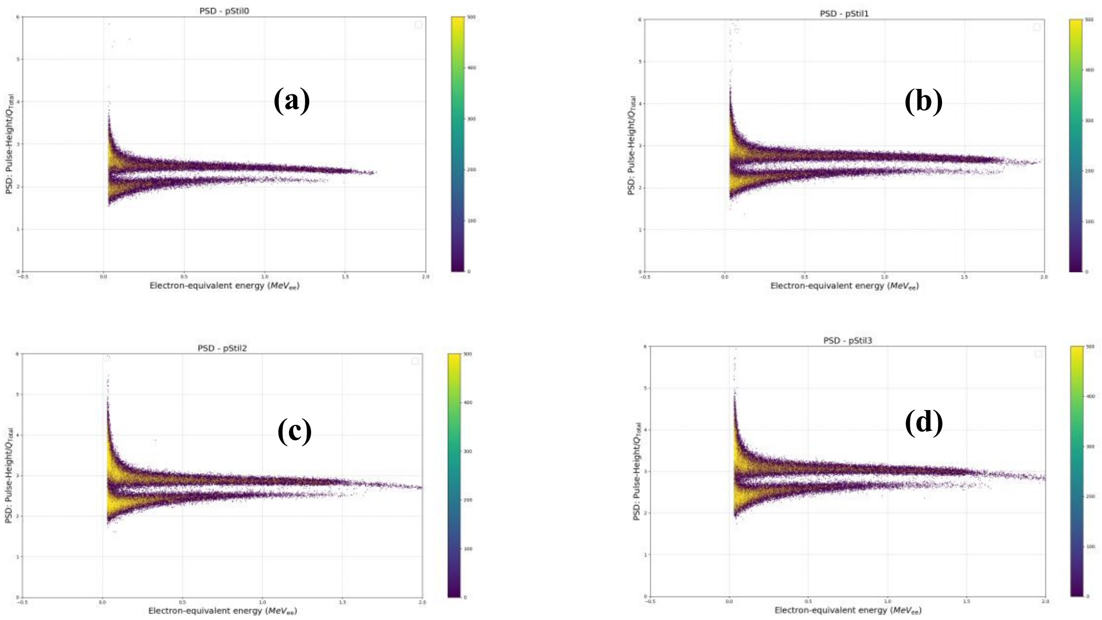

Figure 4. *2D PSD histogram for the four stilbene crystals irradiated with a Am-Be source. PSD (Pulse-Height/Q_{total}) as a function of electron-equivalent energy (MeV), with a pile-up detection threshold of -300 pC and a low energy threshold of 50 keV. PROTEUS-pStil0 (a), INRAD-pStil1 (b), INRAD-pStil2 (c), INRAD-pStil3 (d).*

Pulse Shape Discrimination (PSD)

Stilbene crystals, due to their pronounced Pulse Shape Discrimination capabilities, allow for effective separation of neutron and gamma radiation. In this work, the PSD method involved integrating the total charge over various time windows and comparing the ratio of pulse height to the total charge to improve particle separation (Fig. 4). After evaluation, a fixed 137 ns integration window was selected as the optimal choice. The study validated the excellent PSD capabilities of the stilbene detectors, with similar performance across different crystals. The figure of merit (FOM) was used to assess the PSD performance, showing effective separation in both low and high-energy ranges (Fig. 5, Table 3). Despite challenges in directly comparing FOM results with other studies due to varying scintillator types and electronics, the findings confirm the suitability of stilbene detectors in applications involving PSD.

Table 3. *PSD FOM values calculated for the four detectors in two energy regions.*

	PSD FOM	
	60-360 keV	**800-1100 keV**
pStil0	1.22 ± 0.01	1.64 ± 0.08
pStil1	1.29 ± 0.01	1.69 ± 0.03
pStil2	1.22 ± 0.01	1.86 ± 0.06
pStil3	1.22 ± 0.01	1.60 ± 0.04

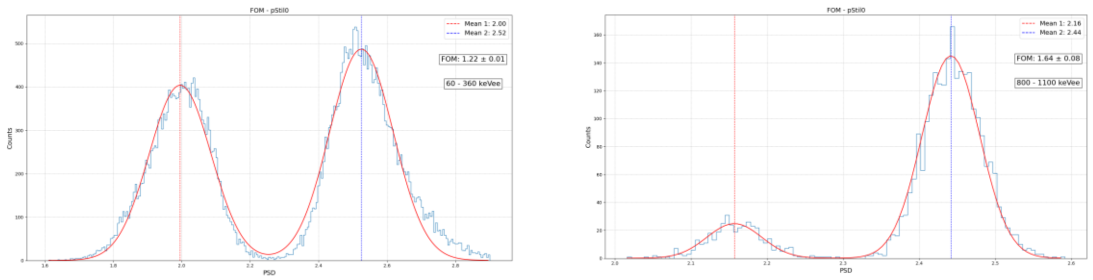

Figure 5. *Example of PSD FOM distributions (blue histograms) for PROTEUS-pStil0, with a double-Gaussian fit (red). (a) Low-energy region 60-360 keV (b) High-energy region 800-1100 keV*

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) [14] was applied in this work to analyze and better understand trans-Stilbene's PSD capabilities. By reducing the data's complexity, PCA helped identify key factors that contributed to the detection process. The results showed that the first principal component (PC1) captured most of the variance, mostly representing energy deposition in the detectors, while the second component (PC2) highlighted features related to pulse shape and pulse duration.

The analysis confirmed excellent separation between neutrons and gamma-rays across all detectors, as reflected in clear clustering patterns in the biplots (Fig. 6). This strong separation, again, demonstrates the detectors' effectiveness in distinguishing different types of radiation. The study also indicated that PCA could complement existing PSD techniques, offering deeper insights into the characteristics of detected signals and enhancing the accuracy of particle classification. Overall, PCA proved to be a valuable tool for improving signal analysis and detection performance in nuclear physics.

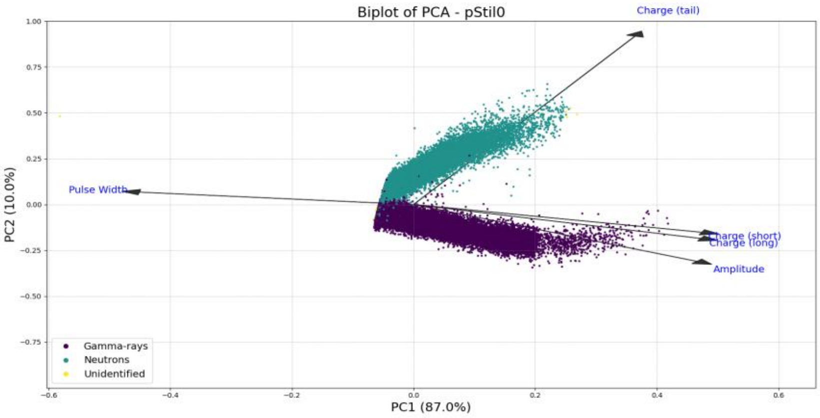

Figure 6. *Example biplot for pstil0. γ-ray events are visualized with purple dots and neutron events with green. "Unidentified" refers to unselected or very high energy signals.*

DISCUSSION & FUTURE IMPROVEMENTS

This research has demonstrated the potential of trans-Stilbene detectors, particularly their advantages in n/γ discrimination, safety, and timing performance. Beyond the core results, several areas present opportunities for future improvements. For instance, further refinements in PSD can be achieved by incorporating additional parameters in PCA, potentially leading to more precise particle separation. Additionally, optimizing the multi-detector array's geometric configuration could further enhance detection efficiency.

A particularly promising direction for future work is the integration of advanced data analysis techniques. By going beyond traditional PSD methods, the implementation of clustering techniques such as Partitioning Methods (K-means, K-medoids) and Hierarchical Methods (Agglomerative), alongside PCA, opens new possibilities for more sophisticated data analysis. These unsupervised machine learning techniques together with supervised ones, when combined with PCA, can uncover deeper patterns in the data, offering a more refined particle classification.

Future research, involving applications in space environment, can take advantages by these analytical techniques in combination with the low power requirements of the setup.

CONCLUSIONS

This research aimed to enhance neutron capture measurements by utilizing trans-Stilbene organic scintillators, which provide a safer and more efficient alternative to traditional C_6D_6 detectors. The trans-Stilbene detectors demonstrated excellent neutron-gamma discrimination, good timing performance, and non-toxic properties, making them highly suitable for precision neutron capture studies critical to understanding stellar nucleosynthesis. The implementation of PCA further improved data analysis, showing potential for broader applications in nuclear physics.

Additionally, a fully symmetrical multi-detector array was developed, optimizing the detector configuration to improve measurement accuracy. Future research should focus on refining these techniques, exploring their applications in different experimental setups, and investigating additional discriminatory parameters to gain deeper insights into particle interactions. This work lays a foundation for enhancing data analysis techniques in nuclear physics, ultimately contributing to a better understanding of fundamental physical processes.

References

[1] Inrad Optics, 181 Legrand Avenue, Northvale, NJ 07647. https://www.inradoptics.com/

[2] Proteus, 120 Senlac Hills Dr, Chagrin Falls, OH 44022. https://proteus-pp.com/
[3] N. Patronis, EPJ Techn. Instrum. 10, 13 (2023); doi: 10.1140/epjti/s40485-023-00100-w
[4] C. Domingo-Pardo et al., Eur. Phys. J. A 59, 8 (2023); doi: 10.1140/epja/s10050-022-00876-7
[5] A. Musumarra et al., for the n_TOF collaboration, EPJ Web Conf. 304, 01009 (2024); doi: 10.1051/epjconf/202430401009
[6] V. Alcayne, et. al., Rad. Phys. Chem. 217 (2024) 111525; doi: 10.1016/j.radphyschem.2024.111525
[7] O. Aberle, et al., Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee; url: https://cds.cern.ch/record/2856350
[8] N. Zaitseva, et. al., Nucl. Instrum. Meth. Phys. Res. A 789, 8 (2015); doi: 10.1016/j.nima.2015.03.090
[9] D. Papanikolaou, Neutron capture reactions for nuclear astrophysics: development & characterization of an innovative detection setup based on trans-Stilbene organic scintillators; url: https://olympias.lib.uoi.gr/jspui/handle/123456789/38242
[10] D.M. Castelluccio, and the n TOF Collaboration; url: https://cds.cern.ch/record/2894839/files/INTC-I-274.pdf
[11] C. Massimi, Proposal CERN-INTC-2024-006; INTC-P-689, https://cds.cern.ch/record/2886127
[12] Cristian Massimi, and the n_TOF Collaboration, EPJ Web of Conferences 275, 01009 (2023); doi: 10.1051/epjconf/202327501009
[13] PS1807 Data Sheet Photomultiplier Power Base (Negative), https://www.sens-tech.com/wp-content/uploads/2023/03/senstech-PS1807-v1.pdf
[14] I. T. Jolliffe, Principal Component Analysis, Second Edition, Springer Series in Statistics, ISBN 0-387-95442-2