Hyperfine Interact (2019) 240: 64
https://doi.org/10.1007/s10751-019-1607-6

Modern African nuclear detector laboratory

Development of state-of-the-art in-house detector facility at the University of the Western Cape

K. Kapoor[1] · **J. N. Orce**[1] · **K. Abrahams**[1] · **E. Akakpo**[1] · **Z. Bester**[1] · **D. G. Jenkins**[2] · **K. L. Jordaan**[1] · **M. Y. Jones**[1] · **M. A. Kamedien**[1] · **R. Lindsay**[1] · **B. Lomberg**[1] · **S. Masango**[1] · **C. Ngwetsheni**[1] · **S. S. Ntshangase**[3] · **N. Radebe**[1] · **S. Triambak**[1] · **J. J. Van Zyl**[4]

Abstract

The upcoming detector facility aims at developing new state-of-the-art particle detectors as well as providing hands-on training to postgraduate students using both analog and digital signal processing from nuclear radiation detectors. The project is two-fold and aims at developing: 1) ancillary detectors to be coupled with the new GAMKA array at iThemba LABS. Of particular interest to our group is the determination of nuclear shapes, which depend on the hyperfine splitting of magnetic substates; 2) PET scanners for cancer imaging using a cheaper technology. Performance of NaI(Tl) inorganic scintillator detectors has been evaluated using PIXIE-16 modules from XIA digital electronics. Gamma-ray energy spectra were acquired from ^{60}Co and ^{137}Cs radioactive sources to calculate the detector resolution as well as to optimize the digital parameters. The present study focuses on improving and optimizing the slow and fast filter parameters for NaI(Tl) detectors which can eventually be used in the list mode of data aquisition.

Keywords NaI(Tl) · Digital signal processing · PIXIE16 · Novel particle detectors

---

This article is part of the Topical Collection on *Proceedings of the International Conference on Hyperfine Interactions and their Applications (HYPERFINE 2019), Goa, India, 10–15 February 2019*
Edited by S. N. Mishra, P. L. Paulose and R. Palit

✉ K. Kapoor
kapoor.phys@gmail.com

✉ J. N. Orce
jnorce@uwc.ac.za

[1] Department of Physics and Astronomy, University of the Western Cape, P/B X17, Bellville, ZA-7535, South Africa

[2] Department of Physics, University of York, York, YO10 5DD, UK

[3] Department of Physics, University of Zululand, P/B X1001, KwaDlangezwa, 3886, South Africa

[4] Department of Physics, University of Stellenbosch, P/B X1 Matieland, Stellenbosch, 7602, South Africa

1 Motivation

The Nuclear Physics academic community in South Africa is historically small and vibrant, with an increasing number of postgraduate students undertaking high education at the Masters and PhD levels. The University of the Western Cape (UWC) consists of diverse student bodies, including the successful MaNuS/MatSci Honours/Masters program, mainly supporting students from historically disadvantaged backgrounds in South Africa. The nuclear physics group at UWC has research interests in fundamental and applied nuclear physics with research grounds at UWC and iThemba LABS in the Western Cape. There is little tradition of in-house development of modern apparatus at historically disadvantaged institutions such as UWC. This limits learning possibilities for undergraduate and postgraduate students to setting up state-of-the-art equipment such as the new GAMKA γ-ray spectrometer at iThemba LABS. The GAMKA array is a project led by UWC – which was awarded the single largest grant (R35M) ever given in a competitive call (Strategic Research Equipment Programme [1]) by the National Research Foundation (NRF) of South Africa – and teamed up with the University of Zululand (UniZulu), Wits, Stellenbosch University and iThemba LABS as the host institution. The GAMKA array will consist of up to 30 high-resolution clover and high-efficiency $LaBr_3$ detectors and will be commissioned in 2020, establishing Nuclear Physics in South Africa at a world-class level.

The upcoming in-house detector facility aims at developing a strand of nuclear applications at UWC and UniZulu in partnership with the University of York (UoY) in the UK. At UWC, the new detector facility has been developed with funding from the Global Funding/Science and Technology Funding Council (STFC) in the UK, and local funding from UWC, NRF and the Department of Science and Technology (DST). The lab is equipped with both analog and digital signal processing units. In order to process the detector signal using the digital processing technique PIXIE-16 modules, XIA-crate, and a PXI-PCI controller were assembled and interfaced to the host PC (http://nuclear.uwc.ac.za/index.php/detector-laboratory/). The PIXIE-16 readouts were visualized using the ROOT based data acquisition package POLL2 (https://github.com/spaulaus/paasslc). PIXIE-16 has been fully power backed with a newly bought powerful UPS to avoid data loss or detector damage in the event of power outages. To test various detectors an efficient vacuum chamber has been designed. The vacuum chamber hosts two rotating arms which will be helpful in particle-γ-coincidence measurements by varying the scattering angles. Figure 1 shows the design for the vacuum chamber, where silicon and NaI(Tl) detectors are shown for representation.

NaI(Tl) detectors has been employed to optimize the digital parameters for signal processing. Testing of detectors was done using various radioactive sources. The main objective of this study is to i) improve and optimize the digital parameters for the optimum performance of the system, ii) identify the key characteristics for the slow and fast filters for further improvement in signal processing using the PIXIE-16. In conventional analog systems, the signals from the detector are processed using the preamplifier and are further shaped, filtered and amplified by the shaping amplifier and then digitized by peak sensing Analog-to-Digital Converter (ADC). Conversion of analog signal to the digital form is done at the very end of the signal processing. However, in the digital pulse processing (DPP), the signal from the detector is converted to the digital form immediately after the preamplifier. This decreases the risk of degradation and instability of detector signal due to the associated analog signal processing. The sampling of detector signals is done by implementing signal

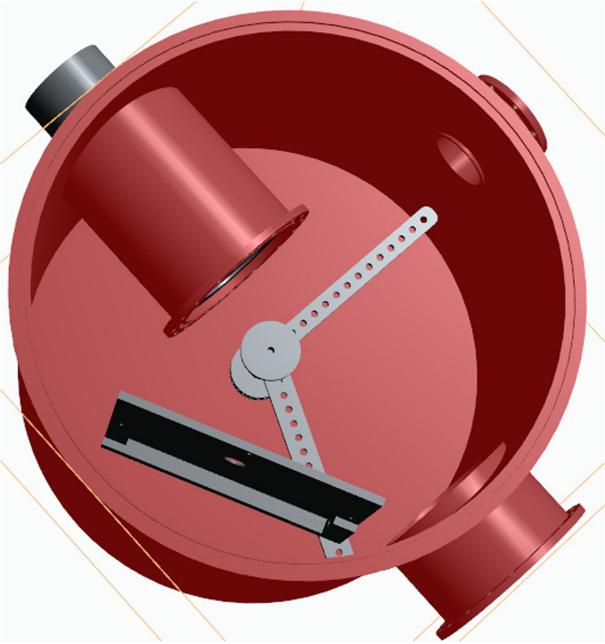

Fig. 1 Sketch of the vacuum chamber designed using SolidEdge (https://solidedge.siemens.com/en/)

filtering functions. These filter algorithms require considerably much less processing time which increases the data acquisition rate while the detector resolution remains constant.

2 Experimental setup

2.1 Detector setup

The primary detector employed in this setup was a NaI(Tl) scintillator detector coupled to the conventional Photo Multiplier Tube (PMT) which has dynode and anode outputs and a high voltage power supply connector to the detector. Output from the anode was connected to the preamplifier (ortec 113) (https://www.ortec-online.com/) which was further connected to the newly assembled PIXIE-16 module for signal processing. NaI(Tl) were employed as they are the most commonly used detectors for gamma ray measurements to get certain timing information between the signals. NaI(Tl) have good detection efficiency because of relatively high density (3.67 $\times 10^3$ kg/m^3) and large atomic number. NaI(Tl) being an inorganic crystals can be grown into different shapes and sizes. NaI detectors with dimension 2.5” × 2.5” were employed in this setup. A high voltage power supply from CANBERRA (model 3002) was used to power the detector (https://www3.nd.edu/wzech/Model-3002D-SS-M2615.pdf). In order to calculate the resolution of the detector, radioactive sources such as ^{60}Co and ^{137}Cs were placed in front of detector. To maximally detect the photons emitted by the radioactive sources they were placed as close as possible to the detector. Experiments were performed in two separate runs with different sources after optimizing the parameters for the respective filters.

2.2 PIXIE-16 digital system

PIXIE-16 is a sixteen channel digital pulse-processing module. At each channel, the input signals are sampled and digitized using the 14-bit in built analog-to-digital converter (ADC). PIXIE-16 communicates using a PXI master module from National Instruments which interfaces with a PCI card deployed on the computer motherboard chassis with suitable PCI card reader (http://www.ni.com/en-in/support.html). The host PC controls the pulse processing module to save the data. Data-acquisition package used for the signal recording and processing utilizes all-digital electronics based on XIA platform (https://github.com/spaulaus/paasslc). The waveform output from the preamplifier is given as an input to one of the channel of PIXIE-16 which takes care for the pulse height analysis, digitized pulse capture and live-time accounting (https://www.xia.com/dgfpixie-16.html). PIXIE-16 module is mainly controlled using the field-programmable gate array (FPGA). FPGA is operated using two trapezoidal filters running concurrently to record the timing as well as the energy information of the signal. The pulse height of the signal is measured with the slow programmable digital trapezoidal energy filter whereas the timing information of the signal is measured with the fast programmable digital trigger filter. All parameter values for the slow (energy) and the fast (timing) filters are adjusted according to the input signal waveform characteristics. Parameters such as threshold, risetime, and flattop are optimized by maximizing the output and input count rate ratio [2]. These are important as they are required for the best estimation of the incoming signal waveform. The threshold was set in such a way so that the noise along the actual signal can be discarded. If the threshold value is set too high, the noise accompanying the actual signal generates peak tailing moreover low energy spectrum can also be rejected. Signal-to-noise ratio was optimised to obtain the best peak resolution. The slow filter covers the larger area of the pulse; it may provide the better estimation of the amplitude of incoming waveform. The risetime value affects peak resolution; it was adjusted until the variation becomes a minimum. So, the value of risetime was set a little higher than the actual risetime of the incoming pulse for the best peak resolution [3]. Similarly, the flattop value was adjusted to get the best charge collection time. Scintillator detectors are characterized by the fast increase of the intensity in the time followed by an exponential decay, so, they require shorter risetime, because the light pulses.

3 Results and discussion

In this study, a careful analysis has been done to optimize the filter parameters for the slow and the fast filters using the two radioactive sources ^{137}Cs and ^{60}Co. ^{137}Cs source decays by beta emission giving the photo-peak at energy 661.7 keV whereas ^{60}Co source decays by beta emission giving two photo-peaks at energy 1173 keV and 1332 keV. Two sources are also considered to be the best candidate for calibration of gamma detectors before the experiments. Figure 2 shows the γ-ray spectra obtained from ^{137}Cs and ^{60}Co radioactive sources. In order to get insight into the effect of various adjustable parameters on the detector resolution it has been seen that the slow and fast filter parameters need to be optimized by considering different set of values. Figure 3 shows one of such case where detector resolution has been studied as function of risetime, where it can be clearly seen that the detector resolution is optimized at $\sim$1.2 μs. For the slow energy filter, the energy risetime was given as 1.2 μs.

Accordingly, various parameters for both the filters were optimized in order to get the best energy resolution. Typically, the signal output from NaI(Tl) detector have risetime

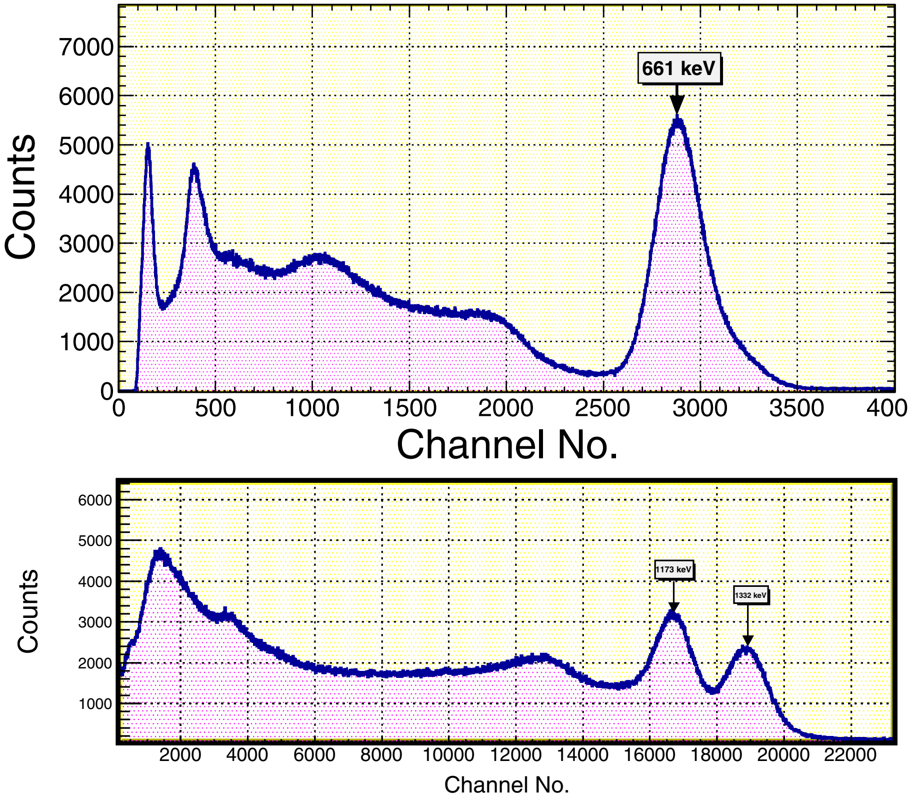

Fig. 2 ^{137}Cs (top) and ^{60}Co (bottom) γ-ray spectra from NaI(Tl) using the new digital DAQ at UWC

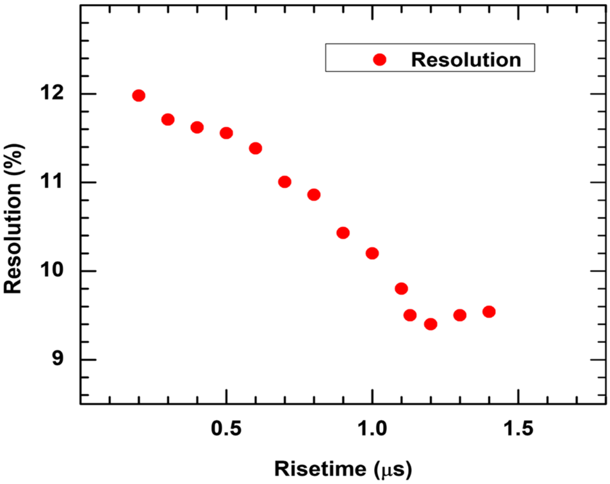

Fig. 3 Resolution (%) as a function of detector pulse risetime (us) for 661 keV photopeak

Table 1 Slow (energy) and fast (timing) filter parameters optimized for NaI(Tl) detector, values are given in μs

Energy risetime	Energy flatop	Trigger risetime	Trigger flatop	TAU
1.12	0.56	0.67	0.2	50

about ~1.0 μs and decay time ~30 μs. In order to fully capture the pulse information and obtain the detector energy resolution, it is required to properly adjust the slow filter parameters and fast filter parameters. The optimized values for this case are given in Table 1. The energy resolution of a detector system is obtained from the peak full width at one-half of the maximum height (FWHM) of a single peak using the following equation:

$$R(\%) = \frac{FWHM}{\sigma} \times 100; \tag{1}$$

here R(%) is energy resolution and σ is the related energy. It will provide the separation for two adjacent energy peaks which will lead to identification of different nuclide in spectrum.

4 Conclusion and future work

Performance of a NaI(Tl) inorganic scintillator detector has been evaluated using a PIXIE-16 module from XIA at the upcoming detector facility at UWC. Gamma-ray energy spectra were acquired with ^{60}Co and ^{137}Cs to calculate the detector resolution as well as to optimize the digital parameters. Slow and fast filter parameters were optimized and the best resolution of around ~9.3% was obtained for a 30 year old NaI(Tl) detector. We intend to further optimize the parameters for both the slow and the fast filters to get the detailed insight into the detector behavior. Also this acquisition system will be tested for γ-γ coincidence and particle-γ coincidence experiments to get the best timing and energy responses. In order to perform particle-γ coincidence measurements we have designed a very efficient vacuum chamber which will become a robust feature of this new detector facility. A Novel state-of-the-art particle detector array will be constructed at the Modern African Nuclear DEtector LAboratory, including PET scanners, ionization chamber and double-sided diamond detectors. As shown in Fig. 4, a team of MSc and PhD students, postdoctoral fellows and faculty staff are currently working on making it happen.

The new Modern African Nuclear DEtector LAboratory will aim at developing state-of-the-art particle detectors, such as ionization chambers, silicon carbide or diamond detectors, that will be coupled to the GAMKA array at iThemba LABS and elsewhere. Of particular interest to our group are the determination of nuclear shapes [4, 5] and related effects such as the nuclear polarizability [6–8]. The model-independent determination of the nuclear charge distribution, or the *intrinsic quadrupole moment* Q_0 in the body-fixed frame of reference, requires the use of rotational invariants and a bountiful set of matrix elements [9, 10]. However, the magnitude and sign of the spectroscopic or static quadrupole moment, Q_S, i.e. the charge distribution of the nuclear shape in the laboratory frame, for excited states with $J \neq 0, \frac{1}{2}$ can be determined using the *reorientation effect, RE*, in Coulomb-excitation measurements. The Coulomb interactions between projectile and target generates a time-dependent hyperfine splitting of the magnetic substates [11] and yields the determination of diagonal matrix elements, which are directly related to Q_S values. A new ionization chamber [12] will be the first apparatus to be developed for Coulomb-excitation experiments

Fig. 4 Some of the group members being involved in the development of state-of-the-art particle-detector laboratories at UWC and UniZulu

coupled with the GAMKA array, which will used to monitor the evolution of the beam composition throughout the experiment, and to determine the target thickness and beam energy losses through the target.

Acknowledgements We are highly thankful to all contributors to this upcoming detector facility at the University of the Western Cape, including Rosita De Oliveira (Finance), Chantal Dreyer (Budgets), Rene Peacock (International Payments), Chantal Keeble, Lucien Ryan, Layan Daley, Owen Swanson (Information and Communication Services), Gaironesa Barnes, Johan Cloete (Business & Innovation), and Jeanine Schroeder (Human Resources). We would like to thank S. Paulauskas for providing valuable feedback for the data acquisition, and P. Papka and D. T. Doherty for instrumental support. One the authors K. Kapoor would also like to thank the Science and Technology Facilities Council in the UK through the Global Challenges Research Fund and the University of York (UK) for providing funding, support and fruitful discussions at various stages.

References

1. GAMKA spectrometer, http://www.nrf.ac.za/media-room/news/nrf-funds-state-art-nuclear-spectrometer-uwc
2. Zhang, W. et al.: Performance evaluation and optimization for a newly developed digital list-mode data acquisition Compton suppression spectrometer. Appl. Radiat. Isot. **81**, 96 (2013)
3. Das, S. et al.: A Compton suppressed detector multiplicity trigger based digital DAQ for gamma-ray spectroscopy. Nuclear Inst. Methods Phys. Res. A **893**, 138 (2018)
4. Orce, J.N. et al.: Reorientation-effect measurement of the $\langle 2_1^+ || \hat{E}2 || 2_1^+ \rangle$ matrix element in ^{10}Be. Phys. Rev. C **86**(R), 041303 (2012)
5. Raju, M.K. et al.: Reorientation-effect measurement of the first 2^+ state in ^{12}C: confirmation of oblate deformation. Phys. Lett. B. **777**, 250 (2018)
6. Orce, J.N.: New formulae for the (-2) moment of the photo-absorption cross section, σ_{-2}. Phys. Rev. C **91**, 064602 (2015)
7. Orce, J.N.: Nuclear polarizability: the sleeping beauty of nuclear physics. In: Proceedings of the 4th South Africa - JINR Symposium (Dubna), "Few to Many Body Systems: Models, Methods and Application", 64 (2015)

8. Ngwetsheni, C., Orce, J.N.: Continuing influence of shell effects at high-excitation energies. Phys. Lett. B **792**, 335 (2019)
9. Kumar, K.: Intrinsic quadrupole moments and shapes of nuclear ground states and excited states. Phys. Rev. Lett. **28**, 249 (1972)
10. Cline, D.: Nuclear shapes studied by Coulomb excitation. Ann. Rev. Nucl. Part. Sci. **36**, 683 (1986)
11. Häusser, O. In: Cerny, J. (ed.): Reorientation Effect, in Nuclear Spectroscopy and Reactions C. Academic, New York (1974)
12. Warr, N. et al.: The Miniball spectrometer. Eur. Phys. J. A **49**, 40 (2013)