Geant4 Investigation of the Alpha-beta-gamma Detector System Used in Medical Imaging, Environmental and Nuclear Site Monitoring

Nuray YAVUZKANAT

Bitlis Eren University, Bitlis-Turkey

In collaborating;
David Jenkins (The University of York), Sefa Ertürk (Niğde Ömer Halisdemir University), Şule Karatepe (Bitlis Eren University)

XIV. International Conference on Nuclear Structure Properties, NSP2021, Selçuk University, Konya-Turkey
02-04 June 2021

1 Phoswich

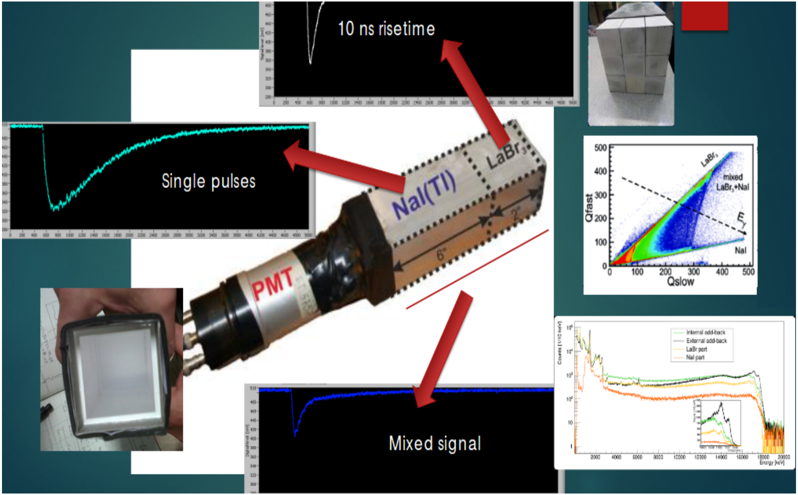
2 Why is it necessary to use an alpha-beta-gamma detector system?
- Nuclear site and environmental monitoring
- Radio-guided surgery (RGS), medical and molecular imaging

3 Geant4 Simulation
- Optimum thickness and materials
- Comparing our results with the literature

4 Conclusion

Phoswich type detector systems

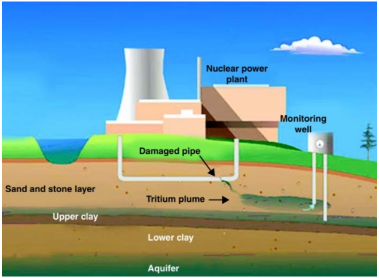
- Measuring different classes of radiation separately or simultaneously and can discriminate from high ambient background radiation.
- Must have different pulse shape characteristics such as rise time and decay times. That gives a great opportunity to distinguish incident radiation, which can be a mixture of charged particles (alpha, beta) and neutrons or gamma rays.
- It also allows for the separation and identification of which events occurred in which scintillator such as the PARIS calorimeter.


10 ns risetime
Single pulses
Mixed signal
NaI(Tl)
LaBr$_3$
PMT
6"
2"
Qfast
Qslow
LaBr$_3$
mixed LaBr$_3$+NaI
NaI
E_γ
Internal add-back
External add-back
LaBr part
NaI part
Energy [keV]

Nuclear site and environmental monitoring

- The environmental monitoring of radionuclide following accidents in nuclear power plants (NPP)-(Fukushima in Japan).
- Monitoring regularly and carefully system inside the NPP. Nuclear waste contains fission products and trans-actinide materials.
- The environment around the NPP to ensure compliance with the basic safety standards. There are two methods to monitor the territory; global (outside the zone) and close monitoring.
- The radiological monitoring have two methods; automatic measuring networks and taking a periodic sample to analyse.

- Monitoring tritium level in groundwater helps to detect the leaks of underground piping.



- The other important disposable radioisotope produced during nuclear fission is Strontium-90 (accidents, leaking from waste or weapon testing).
- Traditional methods (liquid-liquid extraction and chromatography) are processed with hazardous chemicals before the measurement of the activity. In NPP Sr-90 detection must be quickly and easily in order to repeat the procedure many times.

- Large volume of secondary waste and using very hazardous concentration. In the nuclear-decommissioning industry, thousands of samples need to be prepared every year. Needs a new approach to reduce secondary waste production, more rapid, safe as well as cost-effective.
- A novel detection method is Gallium-arsenide (GaAs) photodiode to detect Strontium. Solid-state detectors, not be applicable to detect low energy of the beta particles emitted by tritium. It is also too expensive and radiation damage results in noise in the detector and negatively affect the counting statistics.
- The existing novel detectors are expensive, poor for the detection of a low energy beta, and negatively affected by the radiation. Therefore, it is necessary to develop a new detector with potential for in situ, cost-effective, real-time monitoring in groundwater and more mobile detector which have not been well developed.

Radio-guided surgery (RGS), medical and molecular imaging

- Imaging technologies allow to localize the surgeon in the tumour and give information about its size, shape, and stages.
- pre-operative imaging tools and intra-operative imagine technique are getting more important to provide real-time information of the picture of tumour boundaries.
- radio-guided surgery is a promising field for accurate, sensitive tumour detection, and the most available system. Beta particles inside the tissues have a short range. It requires development of extremely compact devices that can be directly introduced inside the surgical cavity in contact with the surveyed tissues.
- Silicon photomultipliers (SiPMs) have gained a favourable position relative to photomultiplier tubes (PMTs) being compact, low voltage, low power and immune to magnetic fields.

- In nuclear medicine, an alpha-beta-gamma detector has the potential to become a miniaturized beta-gamma imaging probe and modified to use in robotic surgery. Italian research group concluded that the robotic surgery performance and time consumption is better than man-hand operation.

This simulation research can also modify into the development and evaluation of intra-operative miniaturized imaging probes based on two or three layers' scintillators coupled to compact SiPMs as a real-time alpha-beta-gamma monitoring system.

Modelling Geant4 based GATE simulation

Modelling Geant4 based GATE simulation to determine which materials and what thicknesses are the most suitable depending on the radiation type.

1. Yamamato and Ishibashi developed simultaneously monitoring alpha-beta-gamma ray detector system following a nuclear accident or for applications in molecular imaging.

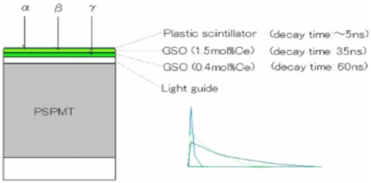
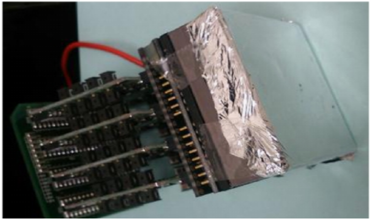


Fig. 1. Schematic drawing of developed alpha–beta–gamma imaging detector.



2 To benchmark the simulation, we reproduced the performance of the Yamamoto et al. detector using the same detector shape and dimension illuminated by the same radioactive sources as shown the detector geometry in Figure 1.

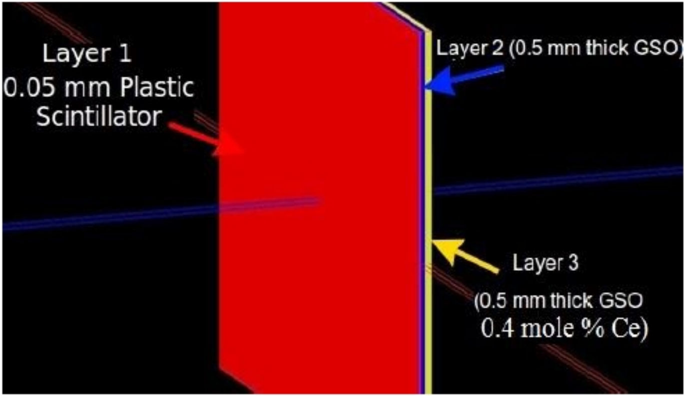
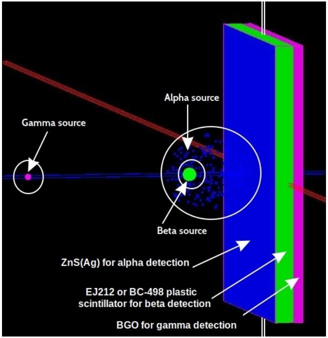


Figure 1. Three different layers described in the simulation; the red layer illustrates to 0.05 mm thick plastic scintillator for detection of the alpha particles. The second layer shows in blue color for beta particles detection and 1.5 mol % Ce doped GSO. The last layer is 0.4 mole % Ce dopped GSO as shown in yellow color.



The first layer (blue) defined as Layer 1 is a scintillation material with 50 x 50 x 0.05 mm^3 dimension. The blue points represent the alpha source (Am-241) with 15 mm diameter and two kBq activity located in front of the detector. The second layer (green) was scintillation material with 50 x 50 x 3.2 mm^3 dimension.

Green spherical point showed for beta particle source (Sr, Y-90) with 2 mm diameter and 100 Bq activity positioned at 1 cm from the detector surface. The last layer (magenta) determined inorganic scintillation with 1.75 mm thickness. Magenta points also represented the gamma source (Cs-137) with 1 mm diameter and 370 kBq activity located at 4 cm away from the detector surface.

Optimum thicknesses and materials result

1. If the first layer thickness is increased in the simulation, beta particle absorption went up inside layer 1. Similar behaviour was also observed for the second and third layers. Increasing the second layer thickness seriously affects the gamma-rays count inside the layer 2. In addition, layer 3 is also affected by annihilation photons (511 keV) occurring after positrons annihilate with electrons. The detection of the gamma-ray inside the third layer could spoil by the annihilation photons. For this reason, the simulation work completed with annihilation photons to optimize the thickness of each layer.

2. The optimum thickness of the first layer material found to be 0.05 mm and that thickness is enough to absorb almost all alpha particles. The Layer 1 material is ZnS(Ag) powder with medium decay time (200 ns). The second layer, EJ212 or BC-498 plastic scintillator, is 3.2 mm thick with the fast decay time (2.4 ns). The last layer to detect gamma-rays could be various inorganic scintillation materials; LYSO, CsI, $LaBr_3$, $CeBr_3$, SrI, GAGG, NaI(Tl), BGO and GSO etc. Some of them are highly hygroscopic materials.
3. In the application, these three different layers have different signal shape characters (different decay time) that will allow applying the pulse shape analysis, resulting in the separation and identification of which events occurred in which layers. Alpha, beta and gamma-rays have different range inside the medium, so these range differences help to show the first layer detects alpha, the second layer detects beta and the last layer detects gamma-rays.

Comparing our results with the literature

Table1. Comparison between GATE simulation and the work of S. Yamamato et al. In the simulation, the result obtained after investigating the best materials and thickness for each layer.

Percentage of relative detected counts for alpha particles			
	$\varepsilon_{exp.}$(%) (Yamamato S. et al.)	ε_{GATE}(%) (present work)	ε_{GATE}(%)¶ (present work with different material)
First Layer	93.5	93.44	99.87
Secand layer	6.1	5.79	0.13
Third layer	0.4	0.77	0
Percentage of relative detected counts for beta particles			
First Layer	0.4	0.32	1.85
Secand layer	87.7	89.24	90.02
Third layer	11.9	10.44	8.13
Percentage of relative detected counts for gamma-rays			
First Layer	0.6	0.95	1.65
Secand layer	60.0	54.71	19.74
Third layer	39.4	50.33	78.61

¶ Different materials with optimum thickness

- The thickness of the first layer material (ZnS(Ag)) was 0.05 mm; that thickness was enough to absorb 99.87% of the alpha particles.
- The second layer, EJ212 or BC-498 plastic scintillator, was 3.2 mm thick and found to have 90.02% efficiency for beta particles.
- To detect gamma-rays, a 0.75 mm thick BGO scintillation material was found to be the best option with its 78.61% gamma-rays efficiency value.
- The detected counts for gamma-rays in the second layer calculated at 19.74 %. No way to remove these counts inside the second layer because of the higher Compton scattering probability of the high energy gamma rays. However, it is highly possible to apply a correction for the gamma detection efficiency of the second and third layers

Conclusion

- No commercially available detector system can measure alpha, beta and gamma-rays at the same time separately with better efficiency and performance.
- Our result is comparable and better than that obtained with a similar detector system in Japan. In the application, each layer will be optically coupled, then the other side of the last layer will couple with the photosensor (PMTs or SiPMs).
- For medical imaging, position-sensitive SiPMs or PMTs must be used to define the position of the events. Proper collimators could be employed to obtain a meaningful image from the three layers detector system.

- The operating principle of this detector will be simple, easily portable and easy to use comprising a combination of novel materials with a state-of-the-art electronic system. It can be used for medical or molecular imaging during surgery or other applications in medicine as a beta-gamma probe.
- The newly designed detector system can also be in direct contact with liquid or water to monitor the radiation inside or around of the nuclear power plant. We have already succeeded to measure directly beta particles emitted by Ga-68 and F-18, used as a PET radiotracer in Hull PET research centre.
- This type of detection system is highly suitable to be applied to nuclear-decommissioning applications such as in situ alpha-beta-gamma detection, which will be mobile, and becoming for real-time monitoring in groundwater as shown a possible detector design in Figure 3.

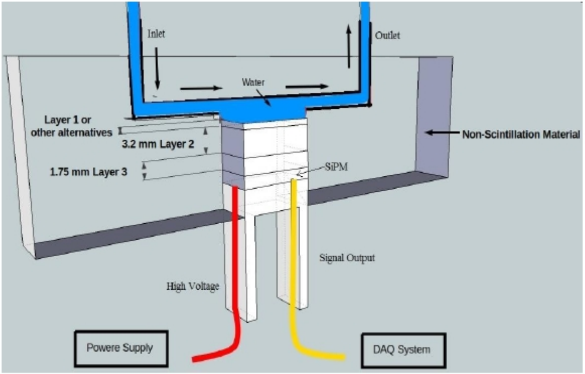


Figure 3. Detector design for monitoring radiation level in water or liquid, which is slightly similar to plastic scintillator-based microfluidic devices developed for measuring positron-emitting radionuclide and successfully patented by the research group of the University of York and University of Hull [1,14]. The first Layer material ZnS(Ag) is a thin powder, and it is commercially available within plastic scintillator. Therefore, it could not damage by liquid or groundwater.

References

[1] Yavuzkanat N., Development of Novel Scintillation Detection Techniques for Use in Nuclear Physics and Medical Applications, Doctor of Philosophy thesis, University of York, 2015.

[2] Seiichi Y., Hiroyuk I., Development of at three-layer phoswich alpha–beta–gamma imaging detector, *Nuclear Instruments and Methods in Physics Research A*, (785) (2015) 129–134.

[3] Kenichiro Y., Shigekazu U., H. G., Simultaneous Alpha, Beta/Gamma, and Neutron Counting With Phoswich Detectors by Using a Dual-Parameter Technique, *Ieee Transactions On Nuclear Science*, 48(4) (2001) 1162-1167.

[4] Efremenkov V. M., Radioactive waste management at nuclear power plants An overview of the types of low- and intermediate-level wastes and how they are handled, *Iaea Bulletin*, 4 (1989) 37-42.

[5] SheenI S. H., Prokofiev G., Extended In-Situ and Real Time Monitoring Task 4: Detection and Monitoring of Leaks at Nuclear power Plants External to Structures, *Argon National Laboratory*, Accessed April (2020).

[6] Turkington G., Kelum A. A. G., James G., Beta detection of strontium-90 and the potential for direct in situ beta detection for nuclear decommissioning applications, *Nuclear Instruments and Methods in Physics Research. A: Accelerators, Spectrometers, Detectors, and Associated Equipment,* (911) (2018) 55-65.

[7] Francesco C., Valerio B., Paolo C., Micol De S., Stefano F., Riccardo F., Alessandro G., Daria M., Carlo M. T., Michela M., Riccardo M., Silvio M., Riccardo S., Teresa S., Giacomo T., Elena S. C., Radioguided surgery with β radiation: a novel application with Ga-68, *Nature/Scientific Reports,* 8 (16171) (2018) 1-9.

[8] Bipin S., Brendan C. S. J., Samta T., Valeriy G., Twyla B., Val L., Steven C., Gerald E., Vivek N., A Hand-Held Beta Imaging Probe for FDG, *Ann Nucl Med.* 27 (3) (2013) 203–208.

[9] Spadola S., Development and evaluation of an intraoperative beta imaging probe for radio-guided solid tumor surgery, Doctor of Philosophy thesis, Université Paris Saclay, 2016.

[10] Mohammad I., Castro I. F. C., Correia P. M. M., Silva A.L.M., Veloso J.F.C.A., Minimization of parallax error in positron emission tomography using depth of interaction capable detectors: methods and apparatus, *IOP Biomed. Phys. Eng. Express*, 5 (062001) (2019).

[11] Francesco C., Matthias van O., Micol De S., Riccardo F., Marta F., Carlo M. T., Riccardo M., Roberto M., Judith olde H., Elena S.C., Florian van B., Henk van der P., Renato V. O., Pim van L., Fijs van L., Silvio M., Robotic surgery using a DROP-IN beta probe-feasibility study with 68Ga-PSMA in prostate cancer specpmens, *Research Square,* (2020).

[12] Seiichi Y., Jun H., Development of an alpha/beta/gamma detector for radiation monitoring, *Review Of Scientific Instruments*, 82 (2011) 1-6, 113503.

[13] Yavuzkanat N., Ertürk S., Investigation of the New Generation Detector System Using in Medical Image, *Aksaray University Journal of Science and Engineering,* 3(2) (2019) 99-111.

[14] Mark D. T. Nuray Y., Mohammad M. N. E., Pankaj J., Nathaniel J. B., Nicole P., David G. J., Stephen J. A., Plastic Scintillator-Based Microfluidic Devices for Miniaturized Detection of Positron Emission Tomography Radiopharmaceuticals, *Chemistry A European Journal*, 24 (2018) 13749-13753.