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A Comparison of Experimental Data with Monte Carlo Calculations for Optimisation of the Source-to-Detector Distance in Determining the Efficiency of a $LaBr_3$:Ce (5%) Detector

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***Abstract*—**Cerium-doped lanthanum bromide $LaBr_3$:Ce(5%) crystals are considered to be one of the most advanced scintillator materials used in PET scanning, combining a high light yield, fast decay time and excellent energy resolution. Apart from the correct choice of scintillator, it is also important to optimise the detector geometry, not least in terms of source-to-detector distance in order to obtain reliable measurements and efficiency. In this study a commercially available 25 mm x 25 mm BrilLanCe^{TM} 380 $LaBr_3$: Ce (5%) detector was characterised in terms of its efficiency at varying source-to-detector distances. Gamma-ray spectra of ^{22}Na, ^{60}Co, and ^{137}Cs were separately acquired at distances of 5, 10, 15, and 20cm. As a result of the change in solid angle subtended by the detector, the geometric efficiency reduced in efficiency with increasing distance. High efficiencies at low distances can cause pulse pile-up when subsequent photons are detected before previously detected events have decayed. To reduce this systematic error the source-to-detector distance should be balanced between efficiency and pulse pile-up suppression as otherwise pile-up corrections would need to be necessary at short distances. In addition to the experimental measurements Monte Carlo simulations have been carried out for the same setup, allowing a comparison of results. The advantages and disadvantages of each approach have been highlighted.

***Keywords*—**BrilLanCe^{TM}380 $LaBr_3$:Ce(5%), Coincidence summing, GATE simulation, Geometric efficiency

I. INTRODUCTION

THE $LaBr_3$:Ce(5%) has superb scintillator characteristics, combining high effective Z and density, fast decay time, emission wavelengths matching that of commonly available photon detectors, and excellent energy resolution (~3% at 662 keV). However, is highly hygroscopic in nature, making it difficult to process, but its commercial availability has been gradually increasing in recent times [1]. $LaBr_3$:Ce (5%) has come of the superior energy resolution it offers [2].

When describing the detector efficiency D one has to take into account four individual aspects: Geometric efficiency *g*, intrinsic efficiency ε, photon detector efficiency *f* and attenuation in the material along the path between source and detector *F* [3].

$$D = g \times \varepsilon \; f \times F \tag{1}$$

As the scintillator crystals paired with the photon detectors do not yield light at a certain frequency but rather light of broader and often multiple wavelength spectra, it is difficult to separate the photon detector efficiency f entirely from the equation. As the wavelengths of the light yielded by the scintillator are not dependent on direction or distance travelled of an individual ionising particle however, it is fair to assume it to be constant and combine it with the internal efficiency of the detector.

The attenuation F can easily be eliminated by not introducing any obstacles into the flight path between source and detector. Attenuation occurring in the source itself as well as in air over short distances is negligible and attenuation by additional parts of the detector (in this case the enclosure) is considered part of the intrinsic efficiency.

Thus the efficiency D of the system is described by two terms: The geometric efficiency g and the intrinsic efficiency, ξ :

$$D = g \times \varepsilon \tag{2}$$

A. Geometric Efficiency

A radioactive point source of activity ξ radiates isotropically, i.e. with equal intensity in all spatial directions. The surface covered by the emitted radiation at a given distance *r* from the source can therefore be described as a sphere with an area of$4\pi r^2$. The radiation flux *I* going through a defined area A in units of rays/s/unit area can therefore be calculated as:

$$I = \zeta \times \frac{A}{4\pi r^2} \tag{3}$$

Thus the decrease in radiation flux per unit area is inversely proportional to the distance *r* squared, in the field of ionising radiation commonly referred to as the inverse-square law. A preliminary estimation of the geometric efficiency of a

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detector can be obtained by simple application of this geometric law.

B. Intrinsic Efficiency

Intrinsic efficiency refers to the detector's ability to absorb incident radiation in the scintillator and convert it into (near) visible light which is then translated into an electrical pulse by the photon detector [4]. The probability of absorption is dependent on composition and effective thickness of the scintillator, as well as the energy of the incident γ-ray. Composition of the scintillator and energy of the γ-rays are inevitably determined, but the effective thickness of the scintillator (assuming the absolute thickness does not vary) is dependent on the angle of incidence, as this determines the distance travelled by the γ-ray in the crystal.

II. EXPERIMENTAL SETUP

A cylindrical 25.0mm diameterx 25.0mm LaBr3:Ce (5%) detector was purchased from Saint Gobain© (BrilLanCe™380). The scintillator was mounted in a 0.5mm container made of aluminium and a mu-metal shield was fitted over the PMT. The PMT had a bialkali photocathode, with maximum quantum efficiency in the wavelength range (170-560nm) suitable for LaBr3:Ce crystals with maximum emission of around 380nm [2]. The PMT was optically coupled directly to the scintillator. The amplifier was set on fine gain 5(the ratio of the signal at the output to the signal measured at the input), and amplifier shaping time 1μs, all used to shape the anode signal. A high voltage power supply (HVPS) provided the detector with positive 600 V according to the manufacturers' specifications. A pulse height analyser was used to record, store, and measure the incoming pulses according to their pulse height. The height of the pulse is usually proportional to the energy of the gamma-ray that enters the detector. Each pulse is consecutively stored in a particular channel corresponding to a known energy. The distribution of pulses in the channels follows the distribution of the energies of the gamma rays incident on the detector. The Genie™2000 basic spectroscopy software was loaded in one of the computers in order to display, record, store and retrieve spectra in channels corresponding to the gamma ray energies. At the end of a chosen counting period, the spectrum was recorded and displayed by using the program. The horizontal axis is the channel number, or gamma-ray energy when the system is calibrated. The vertical axis represents a count of the gamma recorded per channel. The detector was held vertically with graph paper on the table so that the exact position and distance were established.

The spectrum of ^{22}Na was acquired separately for 600s acquisition time. By placing the source on a Perspex holder, the counting measurements of a point source were repeated at various source-to detector distances (5, 10, 15, and 20cm). The background of the sources was acquired for the same acquisition time because the measurement of the absolute efficiencies needs subtraction of the radiation background. To remove the influence of lanthanum self-activity, the background was subtracted. The materials in near proximity of the source detector setup were removed, in order to avoid scattered gamma-rays entering into the detector. The intrinsic and detection efficiency of the LaBr3:Ce detector were measured and compared with the Monte Carlo simulation for the same setup.

III. MONTE CARLO SIMULATION

To compare the experimental data against simulation, Monte-Carlo simulations were carried out using the GEANT 4 based GATE 6.2 toolkit [1]. The $LaBr_3$ detector element was modelled according to manufacturer's specifications [5], including the aluminium casing to account for its effect on intensity losses. Single event information was recorded for three calibration bead sources (^{22}Na, ^{137} Cs, and ^{60}Co) on the detector axis at distances of 5, 10, 15 and 20cm from the detector surface, respectively. The number of simulated events was kept similar to the sources used in the experimental setup to provide equal statistic of precision. The ROOT output files were analyzed to obtain an energy spectrum. In this spectrum all photoelectric peaks were fitted with a Gaussian using Origin 8.5 pro.

IV. RESULTS AND DISCUSSION

The initial observation was the change of relative peak intensities when varying the source-to-detector distance. Fig. 1 shows that the intrinsic efficiency is exponentially proportional to the amount of incident energy in detector from different distance. However, the intrinsic efficiency increases with the source to detector distance. The experimental and simulation results show good agreements (Fig 3). Fig. 4 shows that the relative changes in the detection efficiency values were due to the variations in the solid angle subtended by the detector-to-source distance. Therefore, the efficiency measurement was proportional to the solid angle. As the source-to-detector counting geometry is reduced, the sensitivity of the gamma-ray spectrometry is increased, as did the count rate [6]. However, the detector cannot distinguish separate photons emitted within a time interval shorter than the time constant of the detection electronics. As a result, the pile-up increases which means that the signals of the separate emissions are treated as one and do not appear in their respective peaks [7]. Pile-up correction is required in order to have high accuracy measurements of the efficiency [8]. The result obtained for the intrinsic efficiency at 511keV of about 25% could not reproduce an efficiency of 70% stated in the manufacturer's data sheet for this type of scintillator.

TABLE I
INTRINSIC EFFICIENCY FOR DIFFERENT RADIONUCLIDE AT DIFFERENT SOURCE-TO-DETECTOR DISTANCES (EXPERIMENTAL)

Distance (cm)	511 keV	661keV	1173 keV	1274keV	1332keV
5	15.98±0.06	9.84±0.10	4.17±0.10	4.37±0.10	3.99±0.10
10	17.36±0.10	11.57±0.10	5.29±0.20	5.84±0.10	4.54±0.10
15	22.51±0.10	12.25±0.30	5.85±0.30	5.91±0.10	4.55±0.30
20	23.59±0.30	12.56±0.50	5.97±0.40	6.45±0.20	5.74±0.30

TABLE II
THE SIMULATED INTRINSIC EFFICIENCY FOR DIFFERENT RADIONUCLIDES (^{22}NA, ^{60}CO. AND ^{137} CS) AT DIFFERENT SOURCE-TO-DETECTOR DISTANCES

Distance	511 keV	661keV	1173 keV	1274keV	1332keV
5	18.26±0.32	13.07±0.04	6.24±0.10	5.70±0.01	5.24±0.06
10	22.36±0.04	15.79±0.09	7.93±0.20	6.97±0.03	6.57±0.10
15	24.33±0.06	17.34±0.14	8.58±0.24	7.54±0.05	7.38±0.20
20	25.03±0.09	17.58±0.19	9.20±0.49	7.86±0.08	7.82±0.33

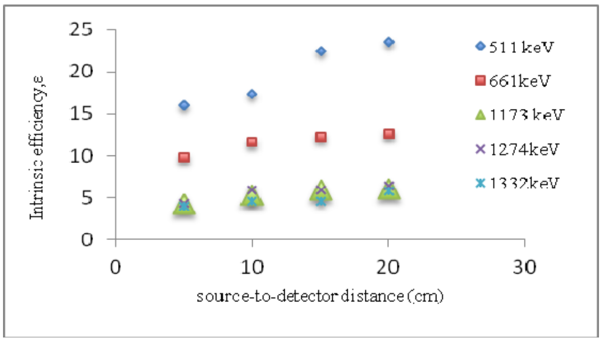

Fig.1 Intrinsic photo peak efficiency in relation to energy (experimental)

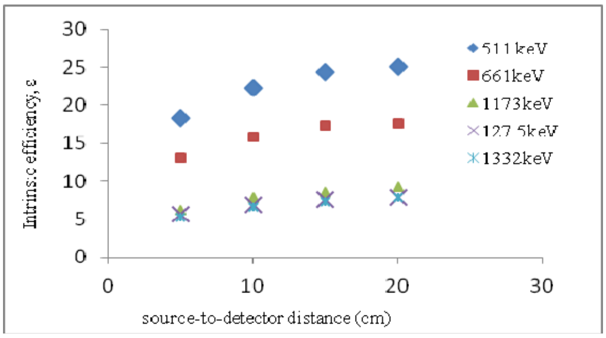

Fig. 2 Intrinsic photo peak efficiency in relation to energy (simulation)

TABLE III
COMPARISON BETWEEN EXPERIMENTAL AND SIMULATED INTRINSIC EFFICIENCY OF LABR$_3$:CE DETECTOR FOR ^{22}NA, ^{60}CO. AND ^{137} CS SOURCES AT 5 CM SOURCE-TO-DETECTOR DISTANCES

Energy(keV)	Experimental efficiency %	Monte Carlo efficiency%
511	15.98±0.06	18.3±0.3
661.6	9.84±0.10	13.07±0.04
1173	4.17±0.10	6.2±0.10
1274	4.37±0.10	5.70±0.01
1332	4.0±0.1	5.24±0.06

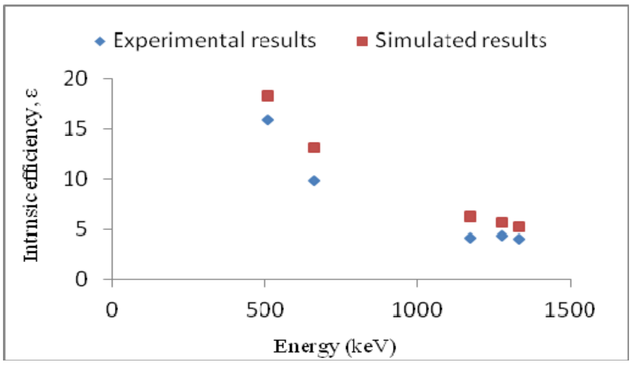

Fig. 3Experimental and simulated efficiency results for the LaBr$_3$ detector at various energies

TABLE IV
THE SIMULATED DETECTION EFFICIENCY FOR DIFFERENT RADIONUCLIDES (^{22}NA, ^{60}CO. AND ^{137} CS) AT DIFFERENT SOURCE-TO-DETECTOR DISTANCES

Distance (cm)	511 keV	661.6 keV	1173 keV	1274 keV	1332 keV
5	0.28±0.04	0.08±0.02	0.20±0.07	0.09±0.01	0.08±0.09
10	0.08±0.01	0.02±0.01	0.06±0.03	0.03±0.07	0.02±0.03
15	0.04±0.01	0.01±0.09	0.02±0.02	0.01±0.04	0.012±0.03
20	0.02±0.08	0.01±0.08	0.01±0.01	0.008±0.04	0.007±0.03

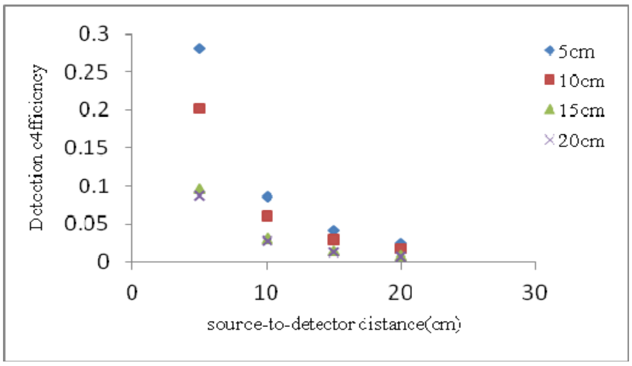

Fig.4 The simulated detection photo peak efficiency in relation to energy

TABLE V
DETECTION EFFICIENCY FOR DIFFERENT RADIONUCLIDES AT DIFFERENT SOURCE-TO-DETECTOR DISTANCES (EXPERIMENTAL)

Distance (cm)	511 keV	661 keV	1173 keV	1274.5 keV	1332 keV
5	0.24 ±0.08	0.15 ±0.01	0.06 ±0.01	0.06 ±0.02	0.06 ±0.001
10	0.06 ±0.03	0.04 ±0.01	0.02 ±0.06	0.02 ±0.02	0.10 ±0.0004
15	0.03 ±0.02	0.02 ±0.05	0.01 ±0.04	0.01 ±0.02	0.20 ±0.0003
20	0.02 ±0.03	0.01 ±0.04	0.005 ±0.003	0.006 ±0.001	0.33 ±0.0003

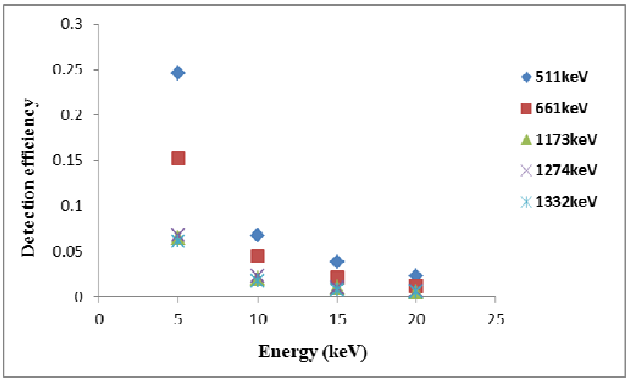

Fig. 5 Variation of detection efficiency with source-to-detector distance (experimental)

V. CONCLUSION

It is important to optimise the source-to-detector distance during the detector calibration and collection of data because it could make a significant error in efficiency. A geometric efficiency determined a drop in efficiency with increasing distance as a result of the change in solid angle subtended by the detector. Although high efficiencies were recorded at low distances, however, a systematic error occurs. Therefore, the source-to-detector distance should be balanced between efficiency and pulse pile-up suppression and pile-up correction is required. One of the drawbacks of using the Monte Carlo simulation for calculation of efficiency is the low precision of the simulation due to insufficient information about source and detector description. However, the short time to acquire the simulation events is helpful for testing different geometric setups in comparison with the practical choice of counting times used experimentally. An additional drawback is that the errors in the detector geometry and the solid angle subtended by the detector and the source could have a negative influence on the efficiency measurement; however, it can be quickly checked by simulation.

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