ORIGINAL ARTICLE

A Feasibility Study on Nano-Particle Properties for Signal Generation at NaI(Tl) Scintillation Detectors

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Abstract

Purpose: Scintillators have become a prevalent method for detecting ionizing radiation due to their ability to produce optical photons that serve as the basis for the final signal representing the physical properties of the incident beam. This signal is generated using interface hardware such as photon multipliers or photodiodes, in conjunction with the scintillator body. A feasibility study was undertaken to investigate a new interface and detector body based on nano-technology and nano-particle materials, which could potentially eliminate the need for the current photon multipliers.

Materials and Methods: The study involved simulating various incidence beams to determine the wavelengths and intensities of light photons emitted from a NaI(Tl) scintillation detector. The absorption and scatter phenomena of light photons were then modeled using a discrete dipole approximation code, with silver being proposed as the nano-particle material. The silver nano-sphere was implemented as a cubic array with numerous point dipoles distributed on a cubic lattice. An experimental verification was also performed, using Silver Nanoparticle material in powder form, irradiated by 420 nm visible photons.

Results: Based on the numerical results, it is feasible to use nano-material properties as a replacement for current light multipliers. The experimental results confirmed variations in the frequency of the function generator, which was chosen as a typical signal.

Conclusion: However, concerns may arise regarding the implementation of the necessary hardware to retrieve the produced signal as output from the nano-material component, to represent ionizing beam characteristics.

Keywords: NaI(Tl) Scintillation Detector; Silver Nano-Particle; Light Photons Intensity; Monte Carlo Simulation; Discrete Dipole Approximation; Frequency Signal.

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1. Introduction

Scintillators have gained widespread recognition as the predominant form of ionizing detectors due to their inherent durability and reliability [1-2]. Scintillators are substances that possess the ability to absorb energy from ionizing radiation and subsequently release optical photons, either instantaneously or after a certain delay. This property is known as luminescence and is the base of signal generation in the radiation detection field [1]. To do this, some dedicated hardware is coupled to Scintillators such as Photocathode or Photo Multiplier Tube (PMT) [3]. Following the generation of the signal, it undergoes a thorough analysis, post-processing, and counting procedure to yield comprehensive information regarding the beam irradiation. Recently, several efforts have been made to develop various types of scintillation detectors [4] due to their wide applications ranging from medicine to industry and modern physics developing studies [5-12]. Moreover, current studies on scintillators material and geometry have caused great improvement in signal quality and their restrictions reduction [2, 13]. Sodium Iodide activated with thallium (NaI(Tl)) is a widely used scintillator that is highly regarded for its ability to measure radiation. Its exceptional light yield, rapid decay time, affordability, and dependable temperature stability make it an excellent choice for use as a counter and spectrometer. NaI(Tl) is an advantageous material in this field and is highly regarded by experts [14, 15]. It should be noted that Thallium is added for more activating of NaI scintillator crystal and hence increasing detector yield [1]. To produce a conclusive indication, it is a common practice to combine a PMT with each scintillator to quantify the visible light emissions from the detector crystal body. There are several types of high-performance PMTs and photocathodes tailored to different forms of ionizing radiation, each featuring distinct shapes and configurations [16]. The PMT is a critical component in the process of multiplying light photons to generate the necessary signal through the application of high voltage. However, the use of a PMT presents several challenges. These challenges include issues related to the geometrical shape of the tube, variations in gain with counting rate, as well as the high voltage supply and voltage divider. These limitations make it difficult to utilize the PMT for certain advanced medical imaging applications [1, 17].

The objective of this study is to assess the efficacy of Nano-materials in combination with the crystal body of scintillation detectors for signal generation. Metallic Nano-Particles, specifically silver and gold, exhibit distinct optical properties called Localized Surface Plasmon Resonance (LSPR), which render them ideal for plasmonic nanoparticles. The LSPR is influenced by the shape, size, and Refractive Index (RI) of the surrounding media. These nanoparticles have been extensively utilized in various applications, such as sensing and biosensing [18, 19].

The primary obstacle we face in our feasibility study is the need to address the current constraints and impediments to the utilization of PMT. To overcome this challenge, we suggest exploring the potential of Nano-particles that are composed of silver and fused with scintillator crystal. Various beams incident with NaI(Tl) scintillator, are taken into account, and produced visible photons are measured using Monte Carlo simulation code. The Discrete Dipole Approximation (DDA) [20] is a robust theoretical method employed to model and compute the optical properties of a 20 nm silver nanosphere (AgNS). In addition to numerical techniques, an experimental setup was developed to investigate the impact of silver nanoparticles on a typical alternating signal. An electrical circuit was assembled, utilizing a function generator as the alternating signal source, and a specialized board to hold a uniform layer of powder silver nanoparticles with specific dimensions. This silver nanoparticle layer was then exposed to 420 nm visible photons, and the resulting changes in the frequency of the alternating signal generated by the function generator were thoroughly analyzed.

Utilizing both experimental and numerical data, it is plausible to explore the implementation of Nano-materials as a replacement for PMT or photocathode to acquire the ultimate signal. However, it is imperative to take into account the potential correlation that exists between the intensity and frequency of visible light produced at the scintillator crystal and the absorbance wavelength of standard Nano-particles.

2. Materials and Methods

2.1. Simulation Setup and Optical Photon Measurement

The Monte Carlo FLUKA code was utilized in this project to expose common incidence beams and track the visible photons produced. FLUKA is a highly reliable Monte Carlo simulation package with extensive applications in various fields, such as medical physics and cosmic ray studies [21-28]. It is capable of computing particle transport and interactions with matter while considering all primary and scattered particles on a case-by-case basis. FLUKA also provides a plethora of user subroutines based on Fortran 77 for users with specific needs. In addition, the program can transport polarized and visible photons, which were considered in this study to follow optical photons emitted from a scintillator crystal. Multiple beams were simulated to identify the optimal light yield based on the beam type and detector shape. After conducting numerous simulations on the crystal size, the reasonable size of the crystal detector that provided the best possible light gain was determined. This point is particularly important in our work since the performance of nano-particles may be influenced by light intensity.

We have developed a simulation environment that considers a cylindrical scintillator crystal with dimensions of 5 cm in diameter and 8 cm in height. The crystal's radial plate is oriented perpendicular to the Z-axis, which represents the direction of beam propagation. The beam is directed towards the cylindrical crystal from a distance of 10 cm away from its radial plate. Our simulation takes into account an annular beam that is irradiated towards the Z-axis. To enhance crystal activation and optimize the light yield, we have employed NaI crystal with 0.11% Thallium in our study. We have simulated different irradiation beams, including gamma, electron, proton, alpha, and muon at varying energy ranges from 100 KeV to 300 MeV scale. This allows us to comparatively examine the light photons generated from the interaction of these beams with the NaI(Tl) crystal.

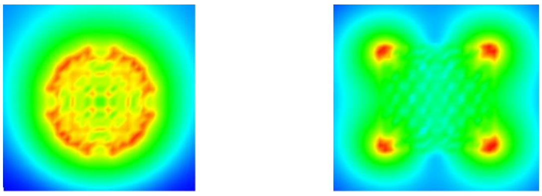
2.2. Discrete Dipole Approximation

The Discrete Dipole Approximation (DDA) proposed by Purcell and Penny Packer and then developed by Draine and Flatau, is a verified code to calculate the scattering and absorption of electromagnetic waves by particles of arbitrary geometry and composition [29, 30]. Recently, the current state of the DDA and its development has been taken into account [31].

In this study, DDA code (DDSCAT Ver. 6.1) is implemented to calculate the extinction, absorption, and scattering spectra as a function of the wavelength of a single AgNS. The nano-sphere was represented as a cubic array of several thousands of point dipoles located on a cubic lattice. The point dipoles are excited by an external field, and their response to the external field and other nearest oscillating dipole neighbors is solved self-consistently using Maxwell's equations. The size of the sphere is defined by an equal volume of a sphere with an effective radius $r_{eff} = (3v/4\pi)^{1/3}$. The refractive index of the silver sphere is assumed to be the same as that of the bulk metal, and the refractive index of the media was 1.5. The plasmonic electromagnetic field intensity (in log scale of $|E|^2/|E_0|^2$) is generated at various wavelengths of excitation.

2.3. Experimental Setup

As mentioned, among the metal nanoparticles, Silver NPs are of great interest because of their potential in optical labels [32-33], contrast enhancement agents [34-35], chemical and biological sensors, and substrates for Surface-Enhanced Raman Spectroscopy (SERS) [36-39]. Silver NPs have novel optical properties due to coherent oscillation of the conduction electrons upon exposure to light impinges, known as Localized Surface Plasmon Resonance (LSPR). This gives rise to enhanced light scattering and absorption, and large local field enhancement, near the NP surface at the resonant condition [40], which can be controlled by modifying the size, shape, composition [41-45], and dielectric environment. Figure 1 shows field distribution after irradiating and absorbing photons with 420nm wavelength of optical photons.



(a) (b)

Figure 1. Field distribution between one (a) and multiple (b) nanoparticles after absorbance of photons with 420 wavelength

An experiment was conducted to observe the impact of optic photon irradiation on Silver NPs. A specially designed electric circuit was employed for this purpose, as shown in Figure 2. The hypothesis put forth was that the emission of these photons was a result of the NaI(Tl) scintillator.

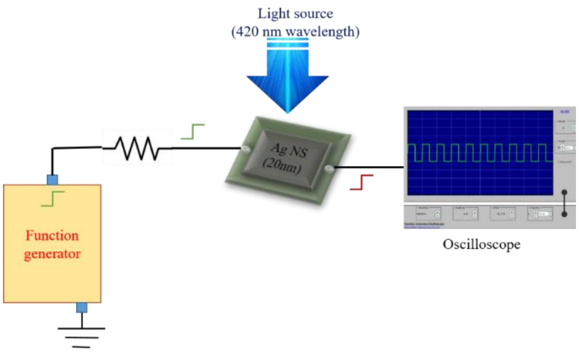


Figure 2. Electric circuit including developed board as placement of a uniform layer of powder shape Silver NP in front of 420nm optical photon

This study involved three apparatus, namely a function generator utilized to produce alternating signals, an oscilloscope employed to examine signal alterations, and a wire board serving as a tray to contain a uniform layer of powdered Silver NP. Upon activation of the function generator, the silver layer was subjected to 420nm optical photons emitted from a scintillation detector. The ensuing alterations were subsequently monitored on the oscilloscope. The study was conducted multiple times, utilizing various measurements of the NP layer and intensities of optical photons.

3. Results

Our team has conducted a rigorous examination of the quantity of light photons emitted by a NaI(Tl) crystal body when exposed to energy beams within a specific range. This evaluation was necessary, as our proposed approach relies heavily on the optical photons emitted by the scintillator. We are pleased to present the results of our analysis in Table 1, which displays the typical outcomes observed for gamma rays ranging from 0.15 to 32 MeV. Our findings demonstrate a clear relationship between the energy of the gamma rays and the quantity of photons generated by the crystal, providing valuable insights for our ongoing research.

Table 1. Maximum number of optical photons (relatively) produced by gamma rays with energies from 0.15 to 32 MeV

Number	Gamma Energy (MeV)	Relative Optical Yield (vs. 0.15 MeV)	Percentage Error
1	0.15	1.00	4.5
2	0.2	1.58	4.9
3	0.3	2.30	4.8
4	0.5	3.20	4.3
5	0.6	4.17	4.9
6	0.7	4.76	4.8
7	0.8	4.76	4.0
8	0.9	5.11	4.1
9	1	5.31	4.9
10	3	16.23	4.3
11	4	21.37	3.7
12	5	30.8	2.7
13	6	36.02	5
14	7	45.72	4.4
15	8	55.23	4.6
16	9	60.72	3.7
17	10	69.14	2.9
18	11	74.00	3.4
19	12	83.17	4.1
20	14	101.04	3.1
21	16	120.61	3.8
22	18	130.51	1.6
23	20	158.21	1.3
24	22	173.23	3.5
25	24	190.00	4
26	26	203.37	3
27	28	216.33	2.9
28	30	216.08	3
29	32	216.33	2.6

In order to provide a clearer understanding of the process, Figure 1 displays a visual representation of the generation of optical photons within crystal body

A. This two-dimensional view is oriented along the Z-axis in the direction of gamma beam propagation, and the colored lines serve to illustrate the path of the optical photons within the crystal volume.

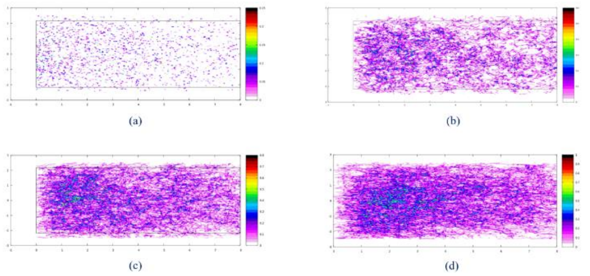


Figure 3. 2D vision of optical photons produced through beam propagation at the middle part of NaI(Tl) crystal body at four: a) 1 b) 10 c) 20 and d) 30 MeV of gamma rays

As seen in this figure, the density of color lines has been increased from 1 to 30 MeV of gamma energies, respectively.

The information furnished comprises coordinates in three dimensions that specify the precise spots where gamma rays collide with the detector body, generating visible light. Additionally, the quantity of energy deposited at each location is also recorded.

In Figure 4, the DDA calculation (DDSCAT Ver. 6.1) presents the results for a single AgNS, showcasing three distinct spectra for extinction, absorption, and scattering across a range of wavelengths. These spectra are generated through the excitation of point dipoles with an external field. The figure reveals that the highest level of extinction is observed at a wavelength of 409 nm, which corresponds to the optical photons produced by the scintillator detector.

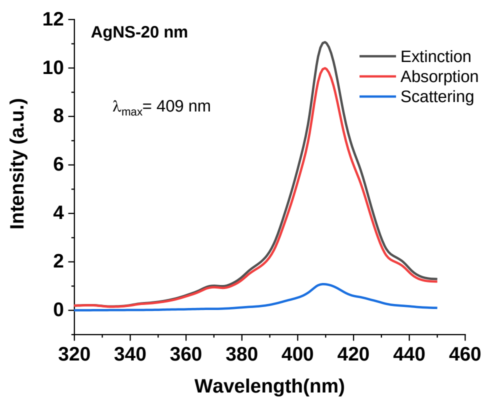


Figure 4. Extinction, absorption, and scattering spectra calculated by DDA for a 20 nm AgNS

The data presented in Figure 5 illustrates the relationship between the frequency of the output alternating signal and the frequency of the input alternating signal in the presence of silver Nanoparticles (NP) within the electric circuit and under optical photon exposure. It should be noted that, in the absence of irradiation, the input and output signal frequencies remain comparable.

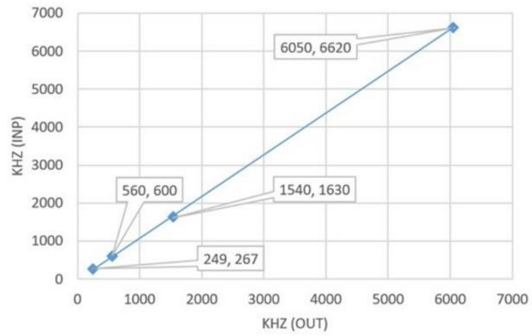


Figure 5. The frequency of output signal versus the frequency of input signal

Figure 6 depicts the impact of the dimension of the silver NP layer on the frequency of the output signal. Observably, as the size of the layer in the square shape expands, the frequency of the alternating output signal also increases remarkably. This phenomenon can be attributed to the distinctive properties of silver NP when exposed to irradiation.

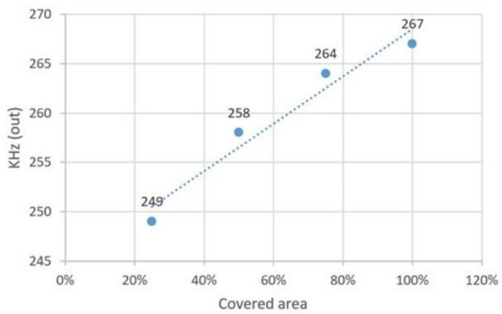


Figure 6. The frequency of the output is influenced by the expansion in the designated area and the number of nanoparticles present

Table 2. 3D coordinate of visible light production (X, Y, Z) and the amount of energy deposition at each event

Number	3D coordinate of each interaction			energy deposition (KeV)	Produced visible light at each coordinate
	X	Y	Z		
1	54	66	25	0.90	×
2	48	48	26	140.90	✓
3	48	49	26	328.67	×
4	48	48	27	238.57	✓
5	48	49	27	71.44	✓
6	49	48	27	244.62	✓
7	49	49	27	263.77	✓
8	49	50	27	46.33	✓
9	49	51	27	63.17	✓
10	50	48	27	28.05	✓
11	50	50	27	14.10	✓
12	50	51	27	0.84	✓
13	48	48	28	43.44	✓
14	48	49	28	6.81	✓
15	49	48	28	346.83	✓
16	49	49	28	3331.91	✓
17	49	51	28	329.11	✓
18	49	52	28	37.55	✓
19	50	48	28	62.14	✓
20	46	51	29	204.44	✓
21	46	52	29	322.023	✓
22	47	52	29	218.36	✓
23	48	49	29	205.40	✓
24	48	59	29	68.06	✓
25	48	50	29	365.40	✓
26	48	52	29	39.88	✓
27	49	52	30	150.60	✓
28	46	50	30	14.30	✓
29	46	51	30	28.31	✓
30	47	49	30	278.53	×
31	47	51	30	43.02	✓
32	48	50	30	62.25	✓

4. Discussion

Lately, there have been significant developments in the fields of nano-material sciences and nanotechnology, both in research and practical applications. Our study focused on the possibility of using nano-material properties as an alternative way to generate signals, in combination with scintillation detectors. After conducting a thorough investigation, we obtained encouraging results, which call for further exploration in this area.

This study delves into an innovative solution to address the challenges and limitations of conventional signal generation methods, such as the utilization of light multipliers. The research centers on the application of Silver and Gold nanoparticles in conjunction with NaI scintillation crystals activated with thallium to produce light. The use of silver nanoparticles presents a distinct advantage as they can absorb low-frequency light photons at 409 nm, which closely corresponds to the wavelength of photons emitted from the NaI(Tl) scintillator.

Various ionizing beams were evaluated for their interaction with a NaI(Tl) crystal using a Monte Carlo simulation code. The objective of this study was to quantitatively assess the intensity of optical photons emitted from the scintillator, which is a crucial parameter for our proposed strategy. Figure 4 presents a comparison of the maximum optical yield for each ionizing beam. Subsequently, the visible lights generated from the crystal were utilized to interact with silver Nano-particle materials, resulting in a potential response.

The data presented in Table 1 indicates that the optical yield of gamma beams displays an increase with energy levels up to 30 MeV. This can be attributed to the greater number of interactions that occur within the crystal-sensitive volume. Notably, the physical attributes of the Scintillation crystal, such as density and dimensions, remain consistent across all energy levels in our simulation study. This finding suggests that varying the type of beam, energy, and detector dimension can produce different densities of light photons. As shown in Figure 3, this phenomenon is exemplified in two dimensions with colored lines representing optical photons produced by photon trajectory along the longitudinal direction of the crystal volume for four different energy levels.

In the second phase of our study, we used DDSCAT 6.1 to simulate the absorption and scattering of light photons by nanoparticles. We modeled a silver nano sphere as a cubic array with point dipoles on a cubic lattice. By exciting these dipoles with light photons, we generated a signal for radiation detection. It's important to note that the absorbance properties of a nanoparticle depend on its size, shape, and material. In the final step, we conducted an experimental test to measure the effect of silver NP under optical photon irradiation. We applied a uniform layer of silver NP powder onto a tray using a simple electric circuit with an alternating signal generator. By altering the parameters, we measured the variations in the signal caused by the presence of irradiated silver NP. Our results (Figures 5, 6) confirmed the significant role played by silver NP in affecting frequency. We tested various sizes of silver layers on the tray and observed the changes in the input and output frequency of the circuit.

This study comprises two essential components, the first being the modeling of the scintillator's response to optical photons generated with the appropriate light density and wavelength. The second component involves examining the nano-materials' response to the produced light photons for proper signal generation. Based on our findings, there may be an opportunity to experimentally couple the latter case with a crystal to create a radiation counter. However, technical challenges may arise in fusing nano-particles included material with the scintillator crystal body. Additionally, we must consider the necessary hardware to obtain the produced signal in the form of electric or magnetic variations from the nano material component, which will be explored in our future studies. Finally, we plan to investigate gold as another potential nano-particle material in future studies.

5. Conclusion

This research endeavor focused on investigating the potential use of Nano-materials, in conjunction with scintillator detectors, to detect and quantify ionizing radiation. Specifically, silver Nano-particles were positioned at the terminus of NaI(Tl) scintillation crystals, and a Monte Carlo simulation code was employed to compute the visible photons generated by the crystal when exposed to varying incident beams. The proposed concept was also put to the test through experimental means, whereby actual silver Nano-particles were placed on an electrical circuit. The findings indicated that the optical photons produced by the scintillator body were indeed effective in stimulating Nano-particles and generating signals. Furthermore, the silver Nano-particles exhibited appropriate absorption and excitation properties in response to the optical photons emitted from NaI(Tl) scintillators, thereby rendering this an area of research with significant potential.

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No conflict of interest applies to the work described in this manuscript.

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