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Impact of Surface Coating Materials and Geometry on the Efficiency of Organic and Inorganic Scintillators: A GEANT4 Simulation Study

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Abstract

This study investigates the impact of various reflective coating materials on the photon counting efficiency of selected organic and inorganic scintillators using GEANT4 simulation toolkit. Reflective coatings, including titanium dioxide, Teflon™ tape and aluminum foil, were applied to both scintillator surfaces to analyse photon collection efficiency by counting optical photons. The simulations were conducted for gamma photon energies of 59 keV, 662 keV and 1173 keV representative of low, medium, and high-energy regimes. The results indicate that aluminum foil provides the highest photon collection efficiency for high-energy gamma photons, while teflon tape exhibits superior performance at lower energies. Multilayer coatings of titanium dioxide and teflon tape show incremental improvements in photon collection, whereas aluminum foil achieves high reflectivity with a single layer, making it a cost-effective and efficient solution. Furthermore, the efficiency enhancement is significantly more pronounced in organic scintillators. These findings provide valuable insights into the selection of optimal reflective coatings for different scintillator materials and radiation energy levels, contributing to the optimization of radiation detection systems used in medical imaging, nuclear physics, and high-energy particle experiments.

Keywords: Plastic scintillators, titanium dioxide, Teflon™ tape, aluminum foil, GEANT4 simulation tool kit

Yüzey Kaplama Malzemeleri ve Geometrisinin Organik ve İnorganik Sintilatörlerin Verimliliği Üzerindeki Etkisi: Bir GEANT4 Simülasyon Çalışması

Öz

Bu çalışma, GEANT4 simülasyon araç setini kullanarak çeşitli yansıtıcı kaplama malzemelerinin seçili organik ve inorganik sintilatörlerin foton sayım verimliliği üzerindeki etkisini araştırmaktadır. Titanyum dioksit, Teflon™ bant ve alüminyum folyo dahil yansıtıcı kaplamalar, optik fotonları sayarak foton toplama verimliliğini analiz etmek için her iki sintilatör yüzeyine uygulanmıştır. Simülasyonlar, düşük, orta ve yüksek enerjili rejimleri temsil eden 59 keV, 662 keV ve 1173 keV gama foton enerjileri için oluşturulmuştur. Sonuçlar, alüminyum folyonun yüksek enerjili gama fotonları için en yüksek foton toplama verimliliğini sağladığını, Teflon™ bandın ise daha düşük enerjilerde üstün performans gösterdiğini göstermektedir. Titanyum dioksit ve Teflon™ banttan oluşan çok katmanlı kaplamalar, foton toplamada kademeli iyileştirmeler gösterirken, alüminyum folyo tek bir katmanla yüksek yansıtma özelliğine ulaşarak maliyet açısından etkili ve verimli bir çözüm haline gelmektedir. Ayrıca, verimlilik artışı organik sintilatörlerde önemli ölçüde daha belirgin bulunmuştur. Bu bulgular, farklı sintilatör malzemeleri ve radyasyon enerji seviyeleri için optimum yansıtıcı kaplamaların seçimi konusunda değerli bilgiler sağlayarak, tıbbi görüntüleme, nükleer fizik ve yüksek enerjili parçacık deneylerinde kullanılan radyasyon tespit sistemlerinin optimizasyonuna katkıda sağlamaktadır.

Anahtar Kelimeler: Plastik sintilatörler, titanyum dioksit, Teflon™ bant, alüminyum folyo, GEANT4 simülasyon araç seti

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1. Introduction

Scintillators are among the most widely used materials in radiation measurement (Kim et al., 2021), with uses ranging from high-energy physics experiments (Denisov et al., 2017) to medical imaging (Van Blaanderen et al., 2023; Kim et al, 2011). These materials operate by converting incident ionizing radiation into photons which are subsequently detected by optical sensors such as photomultiplier tubes (Foord et al., 1969). The scintillation light yield of a scintillator is defined by the number of optical photons generated per unit deposited energy. Although a higher light yield implies a more efficient conversion of ionising energy into photons, it does not mean a higher intrinsic detection efficiency. Whether those photons eventually contribute to an electrical signal depends on their transport through the crystal, reflection losses at surfaces, and the quantum efficiency of the photodetector. Photons can be re-absorbed inside the scintillator or escape through poorly reflective surfaces, both of which significantly reduce the intrinsic detection efficiency. To enhance the intrinsic light-collection efficiency, highly reflective coatings are applied to all outer surfaces of the scintillator. These coatings diffuse or specularly reflect optical photons back into the scintillator bulk, increasing the probability that they eventually reach the photodetector instead of escaping. Some of the reflective materials are already in use including titanium dioxide (TiO_2), Teflon^{TM} tape, and aluminum foil which all boast high reflectivity (Taheri and Peyvandi, 2017; Yamashita et al., 2004; Park et al., 2024).

Advances in computational tools such as GEANT4 (Agostinelli et al., 2003; Allison et al, 2006, 2016) have revolutionized the study of scintillation detectors by enabling detailed simulations of optical processes. Simulations represent a relatively inexpensive and highly flexible alternative to experimental procedures, enabling the testing of various materials, configurations, and geometries not accessible when physical prototyping is relied upon. The importance of these simulations increases in comparative tests of different detector materials. Investigating the effect of different reflective materials on the counting efficiency of different scintillators is much easier through simulations and is instructive for experiments.

This study aims to investigate reflective surface coatings, including TiO_2, Teflon^{TM} tape, and aluminum foil, with organic EJ200 (URL-1, 2025) and inorganic NaI(Tl) (URL-2, 2025) scintillators to understand the effect on the intrinsic detection efficiency. For this purpose, two distinct detector types were coated with three distinct coating materials of varying number of layer, and the impact of the coating materials on the scintillator's photon counting was examined.

2. Materials and Methods

This study examines the effects of reflective coatings on two types of scintillators: EJ200, a polyvinyl-toluene (PVT) based plastic scintillator, and NaI(Tl), a thallium-doped sodium iodide scintillator. EJ200 is recognized for its high-speed light emission, and low density, making it ideal for applications where lightweight materials and fast timing responses are critical, such as particle detection and medical imaging. NaI(Tl) scintillators are widely utilized in applications requiring high sensitivity to gamma radiation, including gamma spectroscopy, environmental monitoring, and nuclear medicine, due to their superior light yield and energy resolution. These two scintillators were chosen to represent organic and inorganic scintillator categories and also due to their comparable wavelengths, allowing a comprehensive evaluation of the impact of reflective coatings on photon counting efficiency under varying coating material properties, geometries and different radiation energies.

2.1 Coating Materials

Three reflective coating materials—titanium TiO_2, Teflon™ tape, and aluminum foil—were selected to investigate their effects on photon counting efficiency. Each material was chosen based on its distinct optical characteristics and relevance to practical scintillator applications. TiO_2, commonly used as a white pigment, is well known for its high diffuse reflectance (URL-3, 2025). When applied as a coating, it can significantly enhance photon collection by increasing light scattering within the scintillator environment (Tarancón et al, 2012).

Teflon™ tape is a lightweight, flexible coating material with high reflectivity, making it a preferred choice for scintillator coatings due to its ease of application and effectiveness in multilayer structures. It is primarily composed of Polytetrafluoroethylene (PTFE), which has unique reflective properties due to its molecular structure and surface properties (Park et al., 2024).

Aluminum foil is a thin, metallic coating material with high reflectivity that perfectly blocks light coming from outside. It is suitable for use in confined spaces and offers a practical solution by ensuring adequate photon reflection. Moreover, their low cost is one of the important advantages of both TiO_2 and Teflon™ tape.

These materials were applied to both organic EJ200 and inorganic NaI(Tl) scintillators in simulation environments to evaluate their influence on the photon counting efficiency as measured by the photomultiplier tube (PMT). Multilayer applications were performed for TiO_2 and Teflon™ tape, while aluminum foil was applied as a single layer. These configurations provided a basis for a detailed study of the effects of reflective coatings on scintillator performance.

2.2 Simulation Framework

The simulations were performed using GEANT4 version 11.2. GEANT4 is an open-source simulation toolkit developed at Conseil Européen pour la Recherche Nucléaire (CERN) which widely used in particle physics, nuclear physics, medical applications and many other fields (Kolcu, 2025; Kandemir et al., 2025; Isazadeh and Saray, 2023). It was developed to simulate the interaction of particles with matter. GEANT4 allows the analysis of both low-energy and high-energy processes by modeling the physical properties of particles in detail. In particular, processes such as the motion of optical photons in matter, scattering, absorption and surface interactions can be simulated in detail with GEANT4. Moreover, the customizable structure of the toolkit allows simulations to be optimized as needed and adapted to various experimental conditions.

2.3 Code Structure

The code structure used in the GEANT4 simulation consists of basic classes that enable step-by-step management of the simulation, data collection and analysis. Geometry definition is performed under the Construction class, where the molecular structure and optical properties of the materials are defined in detail. Density, refractive index and light reflection properties for scintillators and coating materials were added to the model. In addition, the geometry of the system was completed by defining the position and volume information of the dummy defined photo multiplier tube.

The physical processes used in the simulation are structured under the PhysicsList class. The G4OpticalPhysics library was used to model the interactions of optical photons with matter. These processes cover optical phenomena such as reflection, refraction, scattering and absorption. In addition, electromagnetic processes are modeled with G4EmStandardPhysics, while the library is defined for low-energy particle interactions.

The initial conditions of the simulation are defined under the PrimaryGenerator class. In this class, the particle type (gamma photons), initial energy, position, and momentum direction are specified in detail.

Simulation runs were managed with the RunAction class. In this class, the tree structures of the ROOT (Brun and Rademakers, 1997) files where the data will be stored were created and separate files were created for each and the collected data were systematically saved. Event-based analyses were performed in the EventAction class, where the energy accumulated in the specified objects during the event was calculated and the optical photons detected by the photo-detectors were counted and recorded.

Step-based data collection and control operations were performed with the SteppingAction class. This class records the data collected during the simulation steps and checks that the simulation runs according to the specified order. Thus, the necessary data records were created at each step and made ready for analysis.

2.4 Geometry and Structure

EJ200 and Luxium NaI(Tl) scintillators were modeled in detail in terms of their material content and optical properties. The scintillators are defined in a rectangular prism geometry with dimensions of 10 cm × 5 cm × 20 cm. The EJ200 scintillator is modeled as a plastic material based on PVT and the NaI(Tl) scintillator is modeled as a thallium-doped sodium iodide. Both scintillators are characterized by the properties listed in Table 1. The emission spectra of the scintillators shown in Figure 1. Xx were biased to the simulation and gamma photons with an energy of 1 MeV for NaI(Tl) and electrons with an energy of 1 MeV for EJ200 were used to verify and calibrate the performance of the scintillators.

Table 1. Properties of EJ200 and NaI(Tl) scintillators

Properties	EJ200 - Eljen	NaI(Tl) - Luxium
Scintillation efficiency	10000 photons/1 MeV e^-	38000 photons/1 MeV γ
Wavelength of Max. Emission	425 nm	415 nm
Refractive Index	1.58	1.85
Density	1.023 g/cm^3	3.67 g/cm^3

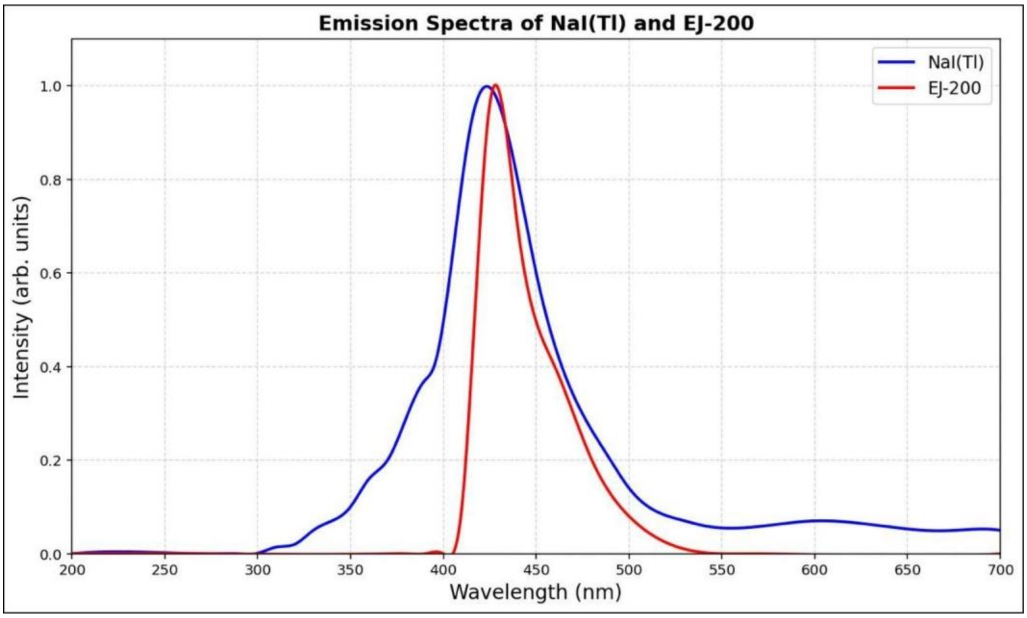

Figure 1. Emission spectra of two different scintillators used in this study.

The coating implementation were carried out in three stages. In the first stage, TiO_2 was applied to the scintillator surface. TiO_2 has a thickness of 36 um, allowing optical photons to scatter randomly from the surface. The surface interactions were defined using the Look-Up Table (LUT) model, with the surface type assigned as dielectric_LUT and the finish as groundtioair. The TiO_2 coating was applied successively starting from the first layer up to the fifth layer and the light collection efficiency was analysed at each layer addition.

In the second stage, the TiO_2 coating was removed and 12 mm wide Teflon^{TM} tape was applied to the scintillator surface. The coating thickness was modelled as 75 um and wrapped in the form of tape, just like in reality. The optical interactions of the Teflon^{TM} tape surface were also defined using the LUT model, assigning the surface type as dielectric_LUT and the finish as groundteflonair. These coatings were applied sequentially from layer one to layer five and the light harvesting efficiency was analysed in detail at each step.

In the third and final step, the Teflon^{TM} tape coatings were removed, and aluminum foil was applied to the scintillator surface. The coating thickness was modeled as 16 um and optical surface interactions were described using the UNIFIED Model. The UNIFIED model is employed to simulate the interaction of optical photons with surfaces, particularly focusing on how surface roughness affects photon reflection. This model conceptualizes a rough surface as an assembly of microscopic facets, each with its own normal vector deviating from the average surface normal as represented in Figure 2. The degree of this deviation is characterized by the parameter SigmaAlpha (σ_α), which represents the standard deviation of the angle between a micro-facet normal and the average surface normal. The surface type was assigned as dielectric_ metal and the finish was selected as polishedfrontpainted to represent the metallic reflection character of the surface. The roughness of the surface was modelled with setSigmaAlpha value of 0.2. This parameter in GEANT4 defines the microscopic roughness of the surface, influencing how photons scatter when interacting with it. A higher setSigmaAlpha value corresponds to a rougher surface, leading to more diffuse scattering, while a lower value represents a smoother surface.

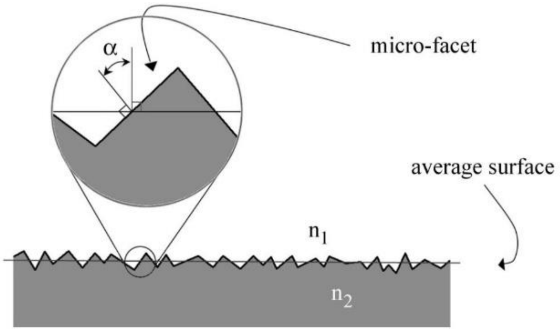

Figure 2. Surface roughness modelling (Janecek and Moses, 2010).

After coating layers had been applied to the surface of the scintillator and their optical properties modeled, boundary surfaces were defined by using the G4LogicalBorderSurface class. This class is crucial in a GEANT4 simulation in defining the optical and physical properties at the interface between two different volumes. In particular, G4LogicalBorderSurface allows the simulation of the optical photon interaction-reflective, refractive, absorptive, or scattering-when a photon encounters a border between materials with different optical properties. In this work, the code was used to represent the transitions between the scintillator and its different coatings in a realistic manner so that the behavior of photons due to each coating layer was well represented.

20000 gamma photons with energies of 59 keV, 662 keV and 1173 keV were directed onto the naked and covered scintillators in each run to evaluate the effects of the coating materials and the number of layers applied. For each energy value, data was collected for every layer applied to both scintillators, effectively enabling a comparative analysis of these energy levels in relation to the performance of the scintillators and their coatings. The results of this detailed evaluation were systematically recorded for further analysis during the data processing stage.

2.5 Data Analysis

The analysis of the simulation data was performed using the G4AnalysisManager class provided in the GEANT4 framework. The data collection and analysis process were designed to focus on event information, photon interactions, and energy deposition in the scintillator. During the analysis process, the data was recorded in N-tuple format. First, an N-tuple called “Hits” was created for information such as the locations where optical photons were detected and their wavelengths, where the column fEvent was defined to record the event ID and the column fWlen to record the wavelengths of the photons. This allows a detailed analysis of the spectral distribution of the photons.

Secondly, an N-tuple named “Scoring” was created to record the total energy accumulated in the scintillator (fEdep) and the total number of photons detected for each event (fPhotonCount). This information is critical for evaluating energy storage performance and photon generation efficiency.

The data collection process started at the beginning of each simulation run with the analysis manager initializing a ROOT file. By assigning a unique file name for each run, data from different simulation conditions were stored independently of each other. During the simulation, event-based and step-based actions were used to save the relevant data in the appropriate N-tuples; at the end of the run, all collected data were written to a file in ROOT format and the file was closed to ensure data integrity. Energy deposition and the number of optical photons detected for EJ200 and NaI(Tl) scintillators under various coating conditions were examined using this structure.

3. Results and Discussion

The effects of different reflective coating materials, including TiO_2, Teflon^{TM} tape, and aluminum foil, on the photon counting efficiency of both organic EJ200 and inorganic NaI(Tl)) scintillators were analyzed using simulations at different gamma photon energies. The PMT counts recorded in simulation for different coatings were given in Table 2, Table 3 and Table 4. The graphical representation of the values helps to see the error bars and the relative effects of different coating layers in Figure 3, Figure 4, and Figure 5.

Table 2. PMT counts for all coatings and its standard deviations for 20000 photons at 59 keV.

Coating	EJ200 PMT Counts	Std. Dev.	NaI(Tl) PMT Counts	Std. Dev.
Uncoated	1026630	21736	11720000	9840
1 Layer TiO_2	2753190	62244	22000000	27800
2 Layer TiO_2	2890849	65356	21829728	27584
3 Layer TiO_2	2905303	65682	21936453	27719
4 Layer TiO_2	2818144	63712	21849579	27609
5 Layer TiO_2	2994278	67694	22023327	27829
1 Layer Teflon Tape	2831400	64025	22060000	17080
2 Layer Teflon Tape	3026766	68442	22065000	17080
3 Layer Teflon Tape	2976522	67306	22107446	17112
4 Layer Teflon Tape	2878648	65093	22042596	17062
5 Layer Teflon Tape	3091668	69910	22149834	17145
1 Layer Aluminum foil	2865060	63453	22530000	15880

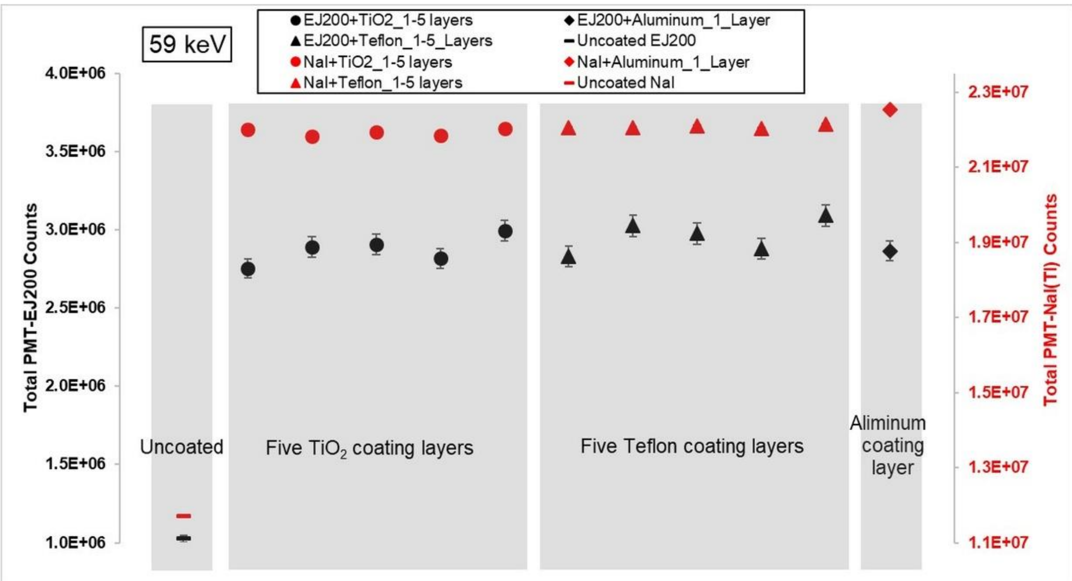

Figure 3. 59 keV gamma photons directed to the scintillator from 5 cm away from middle-top of it. PMT counts were recorded for 20000 gamma events and the standard deviations were calculated.

Table 3. PMT counts for all coatings and its standard deviations for 20000 photons at 662 keV.

Coating	EJ200 PMT Counts	Std. Dev.	NaI(Tl) PMT Counts	Std. Dev.
Uncoated	13706280	232560	78500000	778400
1 Layer TiO_2	34425540	643200	143800000	1409600
2 Layer TiO_2	39059217	729774	149215508	1462685
3 Layer TiO_2	35315748	659832	152528092	1495157
4 Layer TiO_2	35098140	655767	153575960	1505428
5 Layer TiO_2	34885339	651790	144148639	1413017
1 Layer Teflon Tape	37292670	712800	146700000	1301600
2 Layer Teflon Tape	41767790	798336	151717140	1346114
3 Layer Teflon Tape	37764729	721822	155226054	1377247
4 Layer Teflon Tape	37529046	717318	150761132	1337632
5 Layer Teflon Tape	38234592	730803	140414395	1245830
1 Layer Aluminum foil	40589370	798400	142000000	1394800

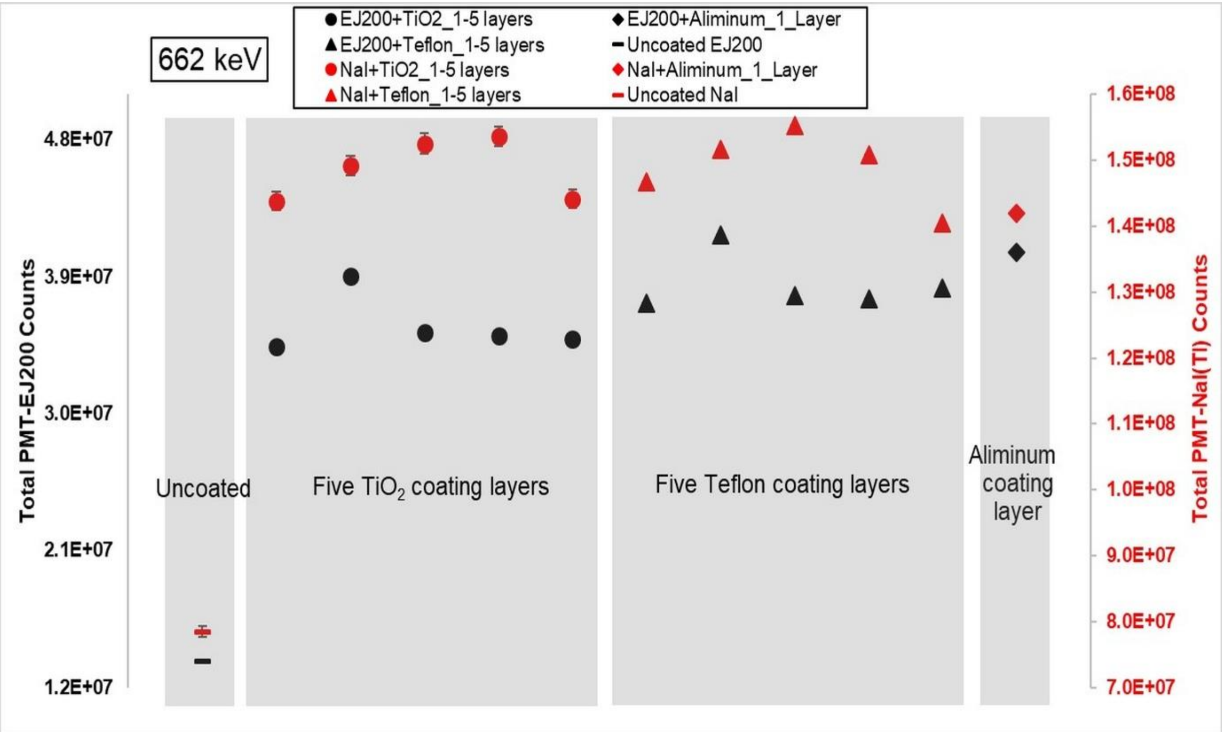

Figure 4. 661 keV gamma photons directed to the scintillator from 5 cm away from middle-top of it. PMT counts were recorded for 20000 gamma events and the standard deviations were calculated.

Table 4. PMT counts for all coatings and its standard deviations for 20000 photons at 1173 keV.

Coating	EJ200 PMT Counts	Std. Dev.	NaI(Tl) PMT Counts	Std. Dev.
Uncoated	23090000	648000	109300000	1992000
1 Layer TiO_2	60320000	1700000	190700000	2733000
2 Layer TiO_2	62214048	1753380	211619790	3032810
3 Layer TiO_2	60297200	1699357	201193282	2883383
4 Layer TiO_2	60236963	1697659	212564727	3046352
5 Layer TiO_2	60995948	1719050	200578202	2874568
1 Layer Teflon Tape	61390000	1575500	202400000	3105000
2 Layer Teflon Tape	63692125	1634581	223960255	3435753
3 Layer Teflon Tape	61777036	1585432	212598751	3261458
4 Layer Teflon Tape	61393328	1575585	222501601	3413376
5 Layer Teflon Tape	61331996	1574011	211461071	3244005
1 Layer Aluminum foil	58440000	1775500	188300000	3098000

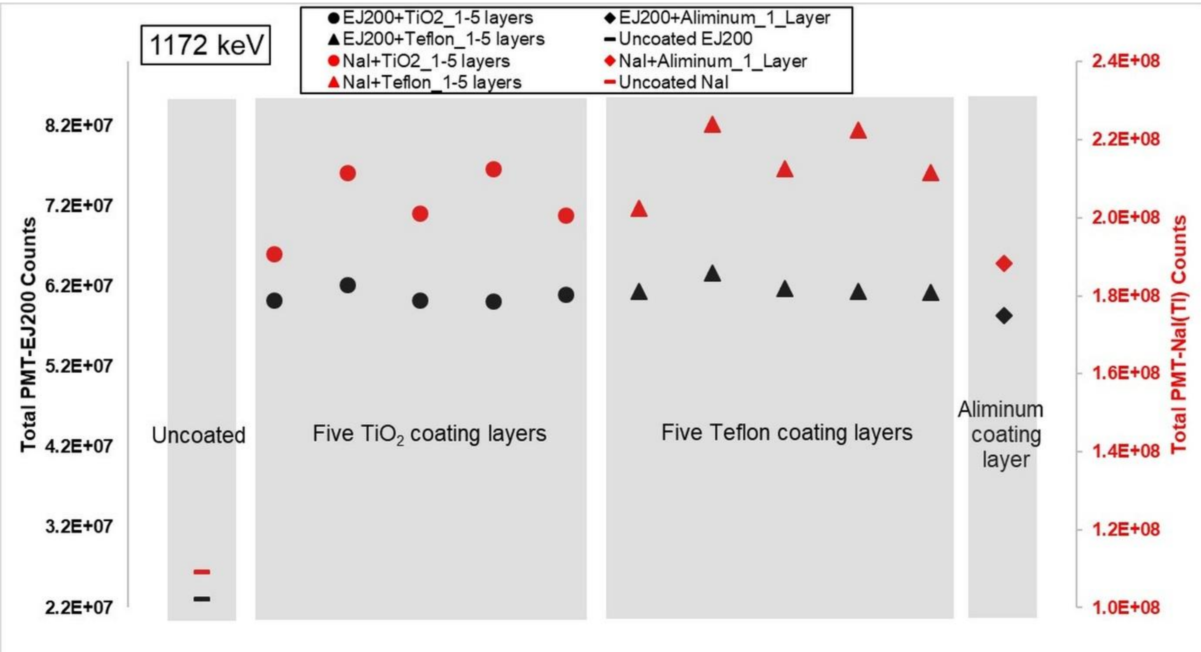

Figure 5. 1172 keV gamma photons directed to the scintillator from 5 cm away from middle-top of it. PMT counts were recorded for 20000 gamma events and the standard deviations were calculated.

At 59 keV, both TiO_2 and Teflon^{TM} coatings significantly improved photon detection efficiency in the EJ200 scintillator, with performance increasing as the number of layers increased. For TiO_2, the photon counts rose steadily from a 168.2% increase with one layer to 191.7% with five layers, while Teflon^{TM} showed a similar trend, reaching up to 201.1% with five layers. This progressive enhancement highlights the importance of multilayer coatings in optimizing light reflection and collection. In contrast, a single layer of aluminum foil provided a 179.1% increase, suggesting high initial efficiency but limited scalability with additional layering. For the NaI(Tl) scintillator, both coatings also improved performance, though to a lesser extent. TiO_2 and Teflon™ coatings achieved increases of 88.0% and 88.9%, respectively, with five layers, whereas aluminum foil achieved 92.2% improvement in a single layer. These results demonstrate that while aluminum can offer strong baseline enhancement, multilayer coatings like TiO_2 and Teflon™ allow finer control and cumulative gains in detection efficiency.

At 661 keV, both TiO_2 and Teflon™ coatings continued to exhibit a cumulative enhancement in photon detection efficiency for the EJ200 scintillator. The photon counts increased from a 151.1% improvement with a single layer of TiO_2 to 205.7% with five layers. Similarly, Teflon™ coatings enhanced performance up to 204.5% with five layers. These trends indicate that even at mid-energy gamma levels, multilayer coatings effectively improve light collection. NaI(Tl) also showed a positive response to coating layers, with TiO_2 and Teflon™ achieving 95.7% and 97.9% increases, respectively, compared to the uncoated configuration.

Single layer of aluminum foil yielded a 95.8% increase in NaI(Tl) and 196.0% in EJ200, suggesting that while aluminum maintains high reflectivity, multilayer dielectric coatings offer more tuneable and scalable improvements.

At 1173 keV, the performance benefit of multilayer coatings was sustained. EJ200 counts increased from 161.2% with one TiO_2 layer to 213.9% with five layers, and similarly from 166.0% to 217.7% with Teflon™. These data affirm that high-energy photons also benefit from enhanced internal reflection and photon guidance provided by multiple reflective layers. In the NaI(Tl) scintillator, coating effects were again notable but less pronounced, with five-layer TiO_2 and Teflon™ coatings achieving 94.6% and 93.7% gains, respectively. The aluminum layer yielded an increase of 72.3% in EJ200 and 72.3% in NaI(Tl), indicating a consistent but less progressive effect. Overall, these findings support the strategy of using multilayer TiO_2 or Teflon™ coatings to fine-tune scintillation photon capture, particularly in polymer-based detectors like EJ200.

The results highlight the advantages of using reflective coatings in scintillator applications. When compared for organic and inorganic scintillators, the coating was found to be approximately twice as effective in organic scintillator materials, regardless of the type of coating. While TiO_2 and Teflon™ coatings show consistent improvements with multilayer applications, aluminum foil emerges as an optimal choice for maximizing efficiency in a single-layer configuration, making it a practical and cost-effective solution for enhancing scintillator performance.

4. Conclusions

In this study, the effects of reflective coating materials such as TiO_2, Teflon™ tape and aluminum foil on the photon counting efficiency of organic EJ200 and inorganic NaI(Tl) scintillators are studied in detail using three different energy levels.

The results obtained show that energy levels are significant in understanding the effects of reflective coating materials. For 59 keV, representing low-energy photons, Teflon™ tape provided the highest photon counting efficiency in the EJ200 scintillator, while aluminum foil coating provided the highest photon counting efficiency in the NaI(Tl) scintillator. But regarding the errors, for 662 keV representing medium energy photons, the highest photon counting efficiency for both scintillators was achieved with Teflon™ tape coating. In the analysis with the 1172 keV photons which represents high-energy photons, aluminum foil was the most effective coating for both scintillators. While multilayer coatings such as TiO_2 and Teflon™ have demonstrated superior performance in photon collection efficiency, the results also highlight the notable effectiveness of a single-layer aluminum foil. At 59 keV, the aluminum layer achieved a 179.1% increase in EJ200 photon counts and 92.2% in NaI(Tl), which are comparable to the gains observed with five layers of TiO_2 (191.7%) and Teflon™ (201.1%). From a practical standpoint, aluminum foil offers distinct advantages in terms of cost-efficiency and ease of application. Aluminum foil stands out because it can be applied quickly and evenly without sophisticated equipment, unlike dielectric coatings that rely on sputtering or layer-by-layer deposition and demand strict thickness and uniformity control. This ease of application makes aluminum especially appealing for large-area scintillators and projects with tight budgets. Although multilayer dielectric stacks can further improve light management through adjustable optical properties and better photon guidance, a single aluminum layer remains a highly competitive choice once fabrication complexity and resource limitations are taken into account.

These findings give an important guide in understanding the interaction of photons of different energy levels with coating materials. The effects of high-energy photons on coating materials were less pronounced compared to low-energy photons but still improved performance. This therefore calls for reflective coatings to be selected carefully, especially in applications sensitive to energy levels.

The effect of coating materials in different energy ranges and with different scintillator geometries could be further investigated in future studies. In addition, experimental validation of the results obtained in this simulation study will help us understand the performance of coating materials based on energy levels more accurately.

Author contribution

E…, M.E: Methodology, software, data analysis, writing, editing.

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Conflict of Interest

The author declares no conflict of interest.

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