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Light transport simulation for a multilayer neutron spectrometer

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**LIGHT TRANSPORT SIMULATION FOR A MULTILAYER NEUTRON
SPECTROMETER**

A Thesis

Presented to

The Faculty of the Department of Nuclear Science

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Natalia Zhuravljova Luckau

May 1999

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ABSTRACT

**LIGHT TRANSPORT SIMULATION FOR A MULTILAYER NEUTRON
SPECTROMETER**

by

Natalia Zhuravljova Luckau

The present work investigates light transport in a scintillation material with the goal of determining an optimal configuration and composition for a compact multilayer neutron spectrometer. Two different neutron-conversion scintillation materials were studied: a polyvinyltoluene- (PVT) based scintillator BC-408, and a BC-702 scintillator, the latter of which consisted of ZnS(Ag) phosphor powder mixed with a lithium compound (enriched to 95% Li-6).

Light transport was simulated and studied using the computer program DETECT, which is a Monte Carlo model of the optical behavior of scintillation detectors. The program estimated the light yield and pulse height distribution for two geometries: a rectangular solid and a hemisphere. Based on the good agreement with actual measurements, the predictive power of the computer model was exploited to optimize an instrument design.

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CHAPTER 1 INTRODUCTION

This thesis presents contributions made to a project that investigated the optimal design of a new type of multilayer neutron spectrometer with a wide energy response range.

Chapter 1 briefly introduces concepts, as well as some of the techniques used for neutron detection. Their advantages and shortcomings are also discussed here, leading to an understanding of the necessity for introducing a new type of detector. This new detector is then studied in detail in the subsequent chapters of the thesis.

1.1 Neutron Spectrometry

1.1.1 Neutron Spectrometry Using Moderating Devices.

Neutrons are detected through their interaction with matter, which results in a secondary radiation such as protons, alpha particles, etc. The energy range of typical neutron fields spans 8 decades (0.025 eV [thermal] to a few MeV, and even higher in the vicinity of high-energy particle accelerators). It is important to evaluate the hazard to humans from neutron radiation with reasonable accuracy, which is the reason why knowledge of the incident neutron energy spectra is essential.

Different techniques have been developed for neutron detection in different energy regions, because the cross section for neutron interactions in most materials is a strong function of neutron energy. Achieving a high sensitivity for a detector of fast neutrons is difficult because typical cross sections for high-energy neutrons are on the order of millibarns. On the other hand, thermal neutron detectors are very sensitive, because cross

sections for thermal neutrons in some materials reach thousands of barns. The inherently low detection efficiency for fast neutrons can be somewhat improved by surrounding the detector with a few centimeters of hydrogen-containing moderating material. The purpose of neutron moderation is to slow down the fast neutrons to thermal energies, where they can be detected with greater efficiency. An instrument based on this technique, the Bonner spheres spectrometer, is briefly described below, inasmuch as the principle of its design is the basis for the neutron spectrometer investigated in this study.

1.1.2 Bonner Spheres as a Model for a Neutron Spectrometer

The Bonner spheres spectrometer is a spherical moderator system that consists of a detector of thermal neutrons, typically a ^6Li scintillator or a ^3He proportional counter, placed at the center of separate polyethylene moderating spheres of different diameters. The capture of thermal neutrons occurs via the $^6\text{Li}(n, \alpha)^3\text{H}$ and $^3\text{He}(n, p)^3\text{H}$ reactions, which are exothermic with Q-value of 4.78 MeV and 765 keV [16] respectively. The peak seen on a pulse height analyzer arises from the capture of thermal neutrons, leading to the aforementioned reactions. In detectors using the above reactions, the large Q-values cause a distinctive peak in the pulse height spectrum, resulting from thermal neutron capture. This enables one to separate the neutron signal from photon background. Bonner spheres of different sizes have different energy response functions. Different shapes and positions of the “peaks” of the response function serve as the basis for using the spheres as a neutron spectrometer. These response functions can be used to “unfold” an unknown neutron spectrum from count rates measured with each sphere. The disadvantages of this method are that one needs to perform separate measurements

for each sphere, and the whole system is quite bulky and cumbersome. In order to avoid the disadvantages mentioned above in the measuring of neutron spectra, a multilayer spectrometer [34] was proposed for further study, with the purpose of optimizing the geometry of such a detector.

1.1.3 Multilayer Compact Neutron Spectrometer with a Wide Range of Energy Response.

The proposed multilayer detector is a large sphere made of a plastic scintillator (polyvinyl toluene) loaded with boron (^{10}B). This material contains hydrogen, and therefore serves both as a moderator and detector. Capture of thermal neutrons (n, α) on ^{10}B generates large light pulses ($Q=2.31$ MeV) from the alphas and therefore discriminates against photon-interactions and recoil protons. The volume of the large sphere is subdivided into several spherical layers, each coated with reflective material and connected by a lightguide to a photomultiplier or a photodiode. Each layer measures its thermal fluence, and the complete set of layer responses thus generated can then be used to unfold the incident neutron spectrum, once each layer's response to neutrons as a function of energy have been measured or calculated. In order to determine a possible configuration for such a multilayer neutron detector, a series of calculations was performed using the neutron transport-modeling program MCNP. The energy response functions of a simulated detector proved to be suitable for the spectra unfolding procedure (see Figures 1 and 2), since the different layers had comparable sensitivities, yet different and distinctive shapes of their response curve.

Figure1. Energy response functions of the three innermost layers.

Figure 2. Energy response functions of the two outermost layers.

The foregoing preliminary investigation suggested the feasibility of this spectrometry technique. Since a critical item in optimizing the design of such a multilayer neutron detector is the light transport, an investigation and analysis of this issue was proposed as the topic of the thesis.

1.1.4 Main Topics of Investigation

The following factors were identified as the major contributors to an optimal instrumental design:

- 1) light transport in the scintillation material;
- 2) signal pulse height as a function of location of the scintillation event in the detector;
- 3) geometry (efficiency) of the spectrometer under study.

Neither of the three factors above will be optimal on its own, it is rather a compromise among these three factors that will be optimal for the overall design.

In order to understand the light transport model, the basic physics principles and the important parameters used in the light transport computer program are presented below.

1.2 Light Transport Physics

1.2.1. General theory.

Light transport is part of the problem of particle detection by scintillators. When an incident particle passes through a scintillator, it deposits energy through interactions with the atomic electrons in the material. A small fraction of this energy is converted into fluorescent light, while the rest is dissipated in the form of lattice vibrations or heat. The fluorescent light production is not directly proportional to the energy deposition and depends on the energy and type of the incident particle, and on its specific ionization. Generally, only a limited fraction of the light produced reaches the surface at which a photomultiplier tube (PMT) or other sensor is located. The collected light is further converted into a corresponding electrical signal [8].

Light-collection conditions affect the energy resolution of the scintillator in two ways. First, the statistical broadening of the response function deteriorates as the number of detected photons that contribute to the measured pulse is reduced. Second, the uniformity of light collection, its dependence on the location of the scintillation event, determines a variation in signal pulse amplitude. In the ideal case all events depositing the same energy, regardless of their location in the scintillator, would give rise to the same pulse amplitude.

One of the tasks in scintillation detection is to achieve good resolution by collecting the possible largest fraction of the light emitted in the scintillation event, and by providing uniformity of light collection throughout the scintillator volume. The following factors can result in the reduction of the light output in the detection:

- 1) Optical self-absorption within the scintillator;
- 2) Light loss at the scintillator surfaces.

Limiting the path length of the light in the scintillation-material layer could minimize the first factor. As to the second point, the light loss and the uniformity of light collection depends mainly on the optical boundaries and their surface finish, and on their geometry. Some general concepts of the light transport physics, employed in most simulations but not described explicitly in the computer code, are presented below.

1.2.2 Principles of Geometrical Optics.

Light propagation in the scintillator media is described by geometrical optics. The light photons emitted due to particle interactions with the scintillator material radiate isotropically in space, with a polarization direction randomly distributed in the plane perpendicular to the photon propagation direction. An assumption is made that the dimensions of the scintillator are large compared to the photon wavelength, so that diffraction can be neglected. Each photon propagates in the detector independently.

1.2.3 Interaction of Light with the Media.

The basic interactions of the ray with the material interfaces obey classical electromagnetic theory (Fresnel's equations) [8,10] in which the photon polarization is included. These interactions are described by the following processes: *attenuation*, *total internal reflection* (TIR), *Fresnel reflection*, (R), and *transmission* (1-R). Since the scintillation light is emitted in all directions, only a small fraction propagates directly to

the photomultiplier tube (PMT). The attenuation of the of light directed exactly towards the PMT is a simple function of the distance traversed in the scintillator bulk material. The attenuation loss is due to the production of lattice vibrations or electronic excitations and to scattering at material density fluctuations, defects etc. In order for the remainder of the emitted light to reach the PMT, it must be reflected one or more times at the surfaces. TIR, Fresnel reflection and transmission take place only at the boundary between two different media. They result in changes of the ray direction, but may also decrease ray intensity due to structure-related losses as well. The two cases are defined as *perfect* and *non-perfect* reflection or transmission respectively. Both cases have been implemented and tested in the DETECT simulation program. Examples are presented in Chapter 5 with $RC=1$, and $RC<1$ respectively.

The optical theory presented below is intended to explain the reflection and scattering models used in the computer simulation.

A. Scattering theory.

Any deviation from an ideal interface upsets the interference effect required for specular reflection and results in surface scattering. A few adjustable parameters used in the surface modeling can give a good approximation to the scattering process.

Scattering problems are most generally described by an integral equation that relates the incident and scattered fields. The key approximations are: an incident plane wave, a scattered plane wave, and an interaction term that couples them, integrated over the

illuminated area of the surface. The interaction term is $P(r)$, where r is the position vector in the surface, $P(r)$, can be factored into system and surface terms

$$P(r) = P_{\text{syst}}(r) * P_{\text{surf}}(r),$$

$P_{\text{syst}}(r)$ is the pupil function of the measuring system and $P_{\text{surf}}(r)$ accounts for the surface imperfections. The second term, $P_{\text{surf}}(r)$, is relevant to the effects of the surface on light collection and will be analyzed here.

B. Surface term.

A surface term, $P_{\text{surf}}(r)$, can be written in the form

$$P_{\text{surf}}(r) = 1 + p(r),$$

1 represents the ideal surface and $p(r)$ is a “perturbation” that describes deviation from a perfectly smooth surface. For a perfect surface, $p = 0$, and the function which describes the intensity of the reflected light shows a sharp spike in the specular direction. In the case of an imperfect surface, $p \neq 0$, and the scattering theory predicts a broadening and weakening of this specular core, plus a scattering-out of the core into larger angles.

C. Surface Modeling.

Surface modeling is based on testing different reflecting and scattering mechanisms. In order to choose the correct surface model, one must be aware of the possible scattering mechanisms and of how they are treated in the computer simulation.

1). Topographic scattering

Surface roughness is the principal source of scattering from the most optical surfaces at visible wavelengths. Surface height fluctuations, Z , result in phase fluctuations of the reflected wavefront.

$$P_{\text{surf}}(r) = e^{i(4\pi/\lambda)\cos\theta_i \cdot Z(r)} \approx 1 + i \cdot 4\pi/\lambda \cos\theta_i \cdot Z(r), \quad (1)$$

Optical-quality surfaces are usually “smooth” in the sense that the exponent above is so small that the two-term expansion on the right is sufficient for describing the scattering outside the specular core. Clearly, the second term on the right is p , the perturbation, responsible for topographic scattering. In the case of rougher surfaces, higher terms in the expansion of the exponential in Equation 1 must be taken into account.

2). *Material scattering*

A perfectly smooth surface ($Z=0$) may still scatter because of fluctuations in its composition or density. For the lack of a better term this is called *material scattering* [5]. This effect can be described in terms of the Fresnel-amplitude reflection coefficient of the surface in the form:

$$P_{\text{surf}}(r) = 1 + [\zeta(r) - \zeta_a] / \zeta_a, \quad (2)$$

Where ζ_a , is the average reflection coefficient. The unity on the right corresponds to a perfect surface and the second term represents the fluctuation about that average, and represents the perturbation, p_m , responsible for scattering.

3) *Defect scattering*

The perturbations responsible for scattering in the surface models described above are usually, as in this simulation, considered to be distributed continuously over the surface. Alternatively, they can be localized at isolated regions of the surface, such as pits or bumps in the topographic case, and patches of different reflectivity in the case of material scattering. A number of exact calculations of scattering from particular defects and structures can be found in the literature [5].

The mechanisms presented above have been approximated in the simulation by choosing a reflection coefficient, RC. For a perfect reflection $RC = 1$. In order to describe the variations in surface quality, a perturbation factor appropriate for a given type of surface finish was implemented in DETECT, after consulting data available in the literature [2,3,6,7,16].

One further approach in modeling surface condition is by the introduction of certain topographic finish parameters, such as the surface roughness for the “UNIFIED” case used in the DETECT simulation program. Descriptions of several such parameters are given below.

1.2.4 Optical Finish Parameters

Optical finish measurements are frequently reported in the literature in terms a few classical topographic finish parameters:

- 1) The rms (root mean square) surface roughness σ ;
- 2) The rms profile slope, μ ;and
- 3) The surface correlation length, l .

These parameters are often used because they are “obvious” measures of quality, and can be directly obtained from raw profile data. A limitation is that their values can depend significantly on the measuring instrument used and do not necessarily represent intrinsic properties of the surfaces being measured.

A simulation of the slab’s polished surface (Chapter 3) was implemented in UNIFIED mode [19] using surface roughness σ , as an adjustable parameter.

CHAPTER 2 LIGHT TRANSPORT SIMULATION USING THE *DETECT* AND *DETECT II* COMPUTER PROGRAMS.

2.1 Introduction to DETECT

The program DETECT [31] is a Monte Carlo model of the optical behavior of scintillation detectors written by G.F. Knoll in the Pascal programming language, which was further modified and translated into the 'C' programming language by TRIUMF [19] under the name DETECT97. It generates individual scintillation photons at point sources with specified coordinates, or in specified portions of the volume of the detector, each with a random propagation vector. It then follows each photon in its passage through the various components and interactions with surfaces, allows for the possible absorption and re-emission by a wavelength-shifting component, and records the fate (absorption, escape or detection) of each photon. The probabilities of these fates are direct ratios of multiple histories involving the simulation of many scintillation photons. Data is also recorded on the number of reflecting surfaces encountered and the photon flight time to detection.

The system to be modeled is completely specified by describing the *geometry*, *surface* properties and *material* of all components used in the system. The configuration file controlling DETECT allows a very general syntax for these specification, which makes possible the representation of complex objects consisting of many components. Any complex system may be modeled, so long as it is possible to separate it into constituent parts consisting of *planar*, *cylindrical*, *conical* or *spherical* objects with arbitrary orientation.

A component is selected from the list of possible *materials*, and its *geometry* is delineated by specifying multiple bounding surfaces. The surfaces may be selected from previously defined planes, cylinders, cones, or spheres, and can be used in either convex or concave orientation. For more flexibility, common non-physical surfaces shared by contiguous elements may be declared as *pseudo-surfaces*, and these are ignored in the tracking.

The optical behavior of real surfaces may be specified by selecting one of a set of previously defined surface *finishes*, such as *polished*, *ground*, *painted* or *metalized* or even a detector surface representing the photocathode or other detecting layer. Surfaces in optical contact are treated using Fresnel's equations of *reflection* and *transmission*, and Snell's law of *refraction*. Within each optical component, specifying a mean distance of photon travel for each process simulates the processes of bulk *absorption*, *scattering*, and *wavelength shifting*. Only one wavelength shift is allowed per history, and is accompanied by appropriate changes in absorption, reflection and scattering properties. Surfaces may either be external, and assumed to be an interface with air, or shared in common with another component.

Once the geometry is defined, a scintillation volume containing or intersecting with the components may be specified, delimiting the required "Generation Box" along with the number of photons produced within this volume. The scintillation photons are uniformly generated throughout the volume, isotropically radiated, and then are tracked on an individual basis until they are absorbed, and detected or escaped from the system. At

each photon reflection or scattering, the program logic determines the new direction of the photon, identifies the component in which it is travelling, and computes the next interaction with a surface. A random sampling is then made to determine if the photon is bulk absorbed, scattered, or wavelength shifted over this path. If none of these processes occurs, the optical properties of the next surface determine whether the photon is reflected, refracted, absorbed, or detected. This process is then repeated for all subsequent paths in the history. A maximum flight time per history is specified to abort those cases in which a photon becomes internally trapped.

After a specified number of histories have been completed, the program reports probability and statistical uncertainty estimate for each of the possible fates. Data are also reported on the probability for wavelength shift, mean age, and mean number of surfaces encountered. These data are separately tabulated for all photons and for just the subset that are ultimately detected. A histogram describing the elapsed time to detection can also be generated. The main flow chart of DETECT is presented in Figure 3.

Figure 3. Main Flowchart of DETECT.

The following is a closer examination of the optical finish options specified by keyword and used in the simulation of the component surfaces:

1. “POLISH”

This option represents a polished surface that may or may not be in optical contact with another component. If no other component is specified, the surface is assumed to interface with a vacuum. Photons incident on the surface are assumed to have random polarization, and they are the first tested for the possibility of Fresnel reflection if a change in refractive index occurs at the surface [31]. This probability is given by Equation 3

$$R = \frac{1}{2} [\sin^2(a-b)/\sin^2(a+b) + \tan^2(a-b)/\tan^2(a+b)], \quad (3)$$

where a and b are the angles of incidence and refraction, respectively. If reflection is selected, the angle of reflection is set equal to the angle of incidence. If reflection does not occur, the photon is transmitted with the complementary probability of:

$$T = 1 - R \quad (4)$$

and is assumed to follow Snell’s law of refraction:

$$\sin(a)/\sin(b) = n_b/n_a, \quad (5)$$

where n_a and n_b are the refractive indices in the incident and transmitted media [31].

Depending on the refractive index change and the angle of incidence, this may result in total internal reflection of the photon back into the incident component. If the surface interfaces with vacuum, and if a diffuse reflector has been specified by including a reflection coefficient in the specification of the surface treatment, the transmitted photon

may be scattered back across the surface. The value of the reflection coefficient is the probability that, if a photon crosses the surface, it is returned to the original medium by Lambertian reflection [31]. In this case, the angle of reflection is independent of the angle of incidence, and is sampled from a distribution given by

$$I(\theta) = I(a)\cos(\theta), \quad (6)$$

where a is the angle of incidence, θ is the angle of reflection and $I(\theta)$ is the light intensity at angle θ . The photon is again refracted as it crosses the surface back into the original medium. Should the reflected photon fail to cross the surface on its first attempt, additional reflection angles are randomly selected until the reflected photon successfully re-enters the original component. Figure 4 illustrates the possible optical processes and their corresponding probabilities for a surface that is polished and coated with a diffused reflector with a specified reflection coefficient of r .

Figure 4. Diffused Reflector with a Specified Reflection Coefficient of r .

2. "GROUND"

This surface specification simulates a roughened or ground optical surface. It is treated in the same way as the polished surface described above, except that the normal to the surface used to define the incidence and refraction angles in Equations 3 to 6 is randomly distributed following a Lambertian distribution around the nominal surface normal. To prevent unrealistic cases in which a photon traveling at an oblique angle could arrive on the wrong side of one of these perturbed surface elements, a test is made of the dot product of the reflected photon direction with the nominal surface normal. For those cases in which the result is negative, a new surface normal is randomly selected until this

dot product is positive. Additionally, a reflection coefficient can be specified to simulate an external diffuse reflector for those photons that pass through a rough surface.

3. "PAINT"

The surface is assumed to be painted with a diffuse reflecting material characterized by reflection coefficients that may be supplied for the primary and shifted wavelength. If random sampling shows that reflection occurs, it is assumed to be Lambertian.

Transmission is not allowed, and consequently jumps in the index of refraction are of no

relevance.

Figure 5. Coordinate system used in DETECT surface models along with the definition of geometrical parameters.

4. "METAL"

The surface is assumed to be smooth and covered with a metallized coating representing a specular reflector. Reflection coefficients may be specified for the primary and shifted wavelength. A random sampling determines whether the photon is absorbed at the surface or undergoes reflection at an angle equal to the angle of incidence. Transmission is treated as in the case "PAINT".

5. "DETECT"

This surface finish represents a photocathode, photodiode, or any other photon detecting layer. As an option, the photocathode may be located on the opposite surface of a thin window of chosen refractive index. Records are kept of the number of primary and waveshifted photons that are detected, so that the results may be easily modified to account for the spectral sensitivity of actual photocathodes at each wavelength.

2.2 Limitations of the DETECT Simulation Program

DETECT does not allow more than one finish type per surface for each component. Therefore, components are required to be segmented into smaller components until this restriction is satisfied. Another important restriction is that a surface of one component in optical contact with a surface of another component must either lie completely within the other surface or envelope it. Although defining two components with a coupling area less than either of the two surfaces in question is syntactically permissible in the description language, problems nevertheless eventually arise during photon tracking. These errors occur due to mishandling of photons that exit one of the components in

contact through the uncoupled area of the surface in question and travel outside the second component, and in fact, outside the defined active volume. An inconvenience of DETECT is the hard coding of the quantum efficiency to be 100%. A solution to this problem, suggested by the authors, is to decrease the number of scintillation photons generated by a factor equal to the quantum efficiency desired. This solution was considered computationally desirable, as it reduces processing time by a factor equal to the quantum efficiency. However, it may also reduce statistics below what is acceptable. The best way would be to reduce the weight of each particle by a factor equal to QE – this way one could get good statistics and correct efficiency.

2.3 Introduction to DETECT II

DETECT II [3] is a version of the DETECT Monte Carlo computer program which was modified specifically to simulate slab geometries. The theory and principles of modeling are the same as presented for DETECT. The user of DETECT II describes the desired system using a set of five input files (*.in). These five files are:

1. *geometry.in* contains information on the object dimensions and materials.

Geometry is described in 3 dimensional Cartesian coordinates using multiple slabs with orthogonal dicing into cells.

2. *material.in* contains a list of materials that correspond to the objects coded with numbers in the geometry file. Each of these materials must have an associated database file with the properties necessary for the simulation of a given medium, such as refractive index, absorption and scattering coefficients, and emission wavelength.

3. *surface.in* contains information about the surfaces present in the model, that are chosen from a list of options, with a default set. These options include flat, rough (for smoothly variant surface profiles), mixed absorber / rough reflector, absorber / specular reflector, and absorber / diffuse reflector (with lambertian emission).

4. *spectrum.in* describes the emission line spectrum of the source.

5. *input.in* contains the number of iterations to be run. It also contains comments describing the parameters and their options.

The results of each program execution are reported in a set of output (*.out) files. f

CHAPTER 3. COMPARISON OF *DETECT II* AND *DETECT* FOR SLAB GEOMETRIES

3.1. Goal of the Experiment

Before the results of the light transport simulation could be trusted, they had to be verified experimentally. The *goals* of the experiment were: a) to validate the computational model; and b) to determine values of critical parameters.

The experiment had two stages. The first stage consisted of measuring detection in a scintillator slab constructed of the PVT based material BC-408 and then simulating the configuration with *DETECT II*. This was done to evaluate the properties of the scintillation material and to verify that the performance of the slab could be successfully modeled using Monte Carlo simulation. The second stage involved switching from the computational model *DETECT II* to *DETECT*, with the purpose of eventually simulating a hemispherical geometry and comparing the two simulations.

3.2 Experimental Method

The method used in this experiment consisted of measuring the intensity I of the light collected by a photomultiplier put at one end of a scintillator slab, when this slab is orthogonally crossed by ionizing particles at various successive distances, d , from the photomultiplier.

The manufacturer, Bicron, characterizes an organic scintillator by determining its Light Attenuation Length [15]. Thus, one of the characteristics of the plastic scintillator measured in this experiment was the Light Attenuation Length, which is defined as the length required to reduce the signal amplitude by $1/e$. It relates most directly to

scintillator sheets and rods having lengths of a meter or more, and when all internal reflections are perfect [6].

Light propagation in the BC-408 organic scintillator was measured using a Plutonium-239 alpha source (activity 638000Bq). The geometry of a slab was chosen to simplify the first stage of the computer simulation. In the second stage the model was expanded to implement the more complex geometrical shapes of various sections of a sphere.

In BC-408 plastic scintillator about 10 scintillation photons are created for each keV of deposited energy. For weakly penetrating particles (like low energy electrons, protons, alphas, and heavy ions) the rate of energy loss increases as the charge and mass of the particle increase, but the efficiency of conversion of the particle energy to scintillation light decreases. For equal energies, a proton will produce only $\frac{1}{4}$ to $\frac{1}{2}$ the light of an electron, while alphas will produce only about $\frac{1}{10}$ the light [6].

3.3 Experimental Setup

A Bicron BC-408 plastic scintillator slab with dimensions of 0.5 x4.0x30.0 cm was coupled to a 5cm diameter PMT as shown in Figure 6a. The scintillator slab itself was tightly wrapped in black paper. Since black paper would prevent alpha particles from reaching the surface of the scintillator, a few 2 cm diameter holes were cut through the paper using the same template. The purpose of the openings was to allow access of the alphas from the Plutonium-239 source, located on the top of the slab, to the scintillator, and to prevent their absorption in the paper. The PMT-scintillator setup was placed in a

tightly closed box, lined inside with black paper, and covered outside with a thick black cloth. The PMT-scintillator setup block diagram is shown in Figure 6b.

Figure 6. a). Schematic view of a Bicron BC-408 scintillator,
b) The PMT-scintillator setup block diagram.

3.4 Procedure

The collected light was measured with the source at distances of 7, 12, 18, 23, 28 cm from the PMT. The following parameters were used in the experiment:

- Voltage – 1800Volts
- Gain – $64 + 0.4 \times 10$
- The counting time for each measurement, including background, was 30 minutes.

The pulses were integrated, and analyzed later using the MCA software MAESTRO (EG&G ORTEC).

3.5 Experimental Results Discussion

In order to measure the attenuation of BC-408 scintillator slab, the integrals of the pulses of the collected light were measured and plotted against the distance between the source and the photomultiplier. The experimental detector was intended to be a plastic scintillator loaded with boron (BC-454) for detection of thermal neutrons via reaction.

The alpha particle and lithium nucleus share the reaction energy Q of 2.31 MeV inversely as their respective masses. Deposition of energy was considered as from a point source, since an alpha particle has a range in the plastic scintillator about 0.01 mm for 2.3 MeV [6]. The number of alpha particles emitted by the source of Pu-239, which has a half-life of 24,119 years, within the time interval of 30 minutes for each measurement was the same for each location tested. Each alpha will generate, on average (this is a stochastic process), the same number of scintillation photons per event. Provided that all the openings in the black paper are rigorously the same, the same number of scintillations should be generated per unit time at each distance.

All scintillation photons from one event contribute to the integral of one pulse in the MCA (when all photons are emitted simultaneously, the result is additive). This means that the pulse height (PH) is proportional to the number of collected photons, and it is a measure of light collection efficiency. Therefore, it is the peak position (channel number) in the MCA spectrum that is of interest in these light attenuation measurements, as indicated in Table 1.

The data obtained from the experiment described above could be treated as attenuation of a beam parallel to the axis of the slab [25]. Then

$$I = I_0 \exp(-d/\lambda), \quad (8)$$

where λ is the Light Attenuation Length of the scintillator. If this were exact, a plot of $\ln(I)$ vs d should be a straight line with the slope $\delta = -\lambda^{-1}$. In fact, the experimental data show the behavior presented in Figure 7, which is a concave curve with a decreasing slope. Explaining this behavior involves the consideration of several additional factors. Assuming the light is isotropically produced, one has to consider that, besides the absorption undergone by direct light rays as described by Equation (8), there are numerous reflections at the boundary surfaces of the scintillator. These reflections imply an effective path length $p' > p$ in Equation (8), and reduction of the light ray intensity at each reflection [25]. The attenuation shown by the experimental data was 15.6% measured over 21 cm which gives a Light Attenuation Length of 135 cm. This result will be compared with that simulated using the Monte Carlo program DETECT II and shown in Figure 8.

At the manufacturer, Bicron bulk attenuation length was measured using 0.5 cm thick x 12 cm wide x 200 cm long sheets of BC-408 coupled by a light guide to the PMT at one end, and with the opposite end of the scintillator blackened, to minimize reflection.

Using this setup, a value of 190 cm for the light attenuation length was measured.

However, when the far end is not blackened, much better performance can be achieved.

The typical bulk attenuation length cited is 380 cm [15]. A simulation of ideally polished

surface (described in section 3.6.2.) returned the value of the attenuation length 372 cm, which is comparable with that specified by the manufacturer, namely 380 cm [15].

The results of the experiment are presented in Table 1 and Figure 7. Average slope was determined for the measured set of points. Error was calculated using a standard deviation percentage of the Net Area Counts.

Table 1. Attenuation by a slab of BC-408 as measured by the experiment

Distance, cm	Peak (Channel #)	LN(Peak)	Slope average
7	417	6.03	0.00841
12	400	5.99	
18	374	5.92	
23	360	5.88	
28	352	5.86

Figure 7. Attenuation by BC-408. Experimental results.

This experiment serves as the benchmark for the light transport model(s).

3.6 Comparison of the Results of the Simulation with DETECT II with Experimental Results

The simulations were originally undertaken with DETECT II because it was available, (before it was possible to obtain a copy of the original DETECT source code), and also because its documentation represented it as being able to model complex geometries. In fact, DETECT II is designed to simulate a slab geometry only, for which purpose it has been used in this study.

3.6.1 Modeling of the Slab Experiment with DETECT II

To model any experiment, it is necessary to find the appropriate parameters that describe and simulate the reality in a satisfactory manner. With these parameters, constrained by reality, a simulation may be successfully applied to reproduce that reality. To model the experiment described above, a set of parameters that describe the collection of the scintillation light at the photomultiplier tube was introduced into the simulation.

The following three parameters are of importance for the light transport modeling [8,11,15,17]:

1. The attenuation length of the material

An attenuation coefficient describes the clarity of the scintillator to its own emitted light. As stated by the manufacturer [6], the attenuation length for a given scintillator might be influenced by:

- a) The thickness and shape of the scintillator;
- b) The reflective properties of the surfaces;
- c) The use of light guides and reflectors.

Data on attenuation length can be found in the manufacturer's specification [6].

2. The surface conditions of the scintillator.

The second factor, the reflective properties of the surfaces, is particularly important for large scintillators. In these geometries over 90% of the light will reach the photomultiplier only after making successful internal reflections. This requires the highest possible polish on the scintillator surfaces in order to maximize total internal reflection of the scintillation light. According to the manufacturer: "Most scintillators are supplied in a finished condition with the surface prepared to optimize light collection. In most applications the scintillator would be polished." [15].

A study of the effects of the surface finish and reflection coefficient on the collected light yield of the slab of the BC-408 scintillator was conducted. The polished ("smooth") option of the surface finish of the scintillator was selected and used in further tests. Reflective properties of the polished surface with the reflection coefficient, RC, was varied over the range of 0.85 to 0.98.

3. Scintillation source

The scintillation source was defined in the 'input' file as follows:

- a) A 'Point source';
- b) Isotropic (semi-plane is possible as well);
- c) With a wavelength sampled from a multiple-line table, using a special case of a monoenergetic wavelength;
- d) With random polarized emission.

3.6.2 Results of the Simulation with DETECT II

1. "Smooth" surface finish.

The first surface simulated with DETECT II was the “smooth” surface, which was supposed to have the properties of an ideally polished surface. The result of the run for 100,000 photons gave an attenuation of 4.3% over 16 cm. This corresponds to a value for the bulk attenuation length of 372cm, compared with that of Bicron’s value of 380cm. The simulation also showed that 98% of photons reached the detector by internal reflections, with only 2% of light escaping the detector. With an “ideally polished” surface the main factor of light loss is absorption in the bulk of the material. Considering the fact that no such perfectly polished surface exists in reality, a non-perfect surface was simulated. In order to approach a non-perfect model, an adjustable parameter, the reflection coefficient, RC, was introduced into the simulation. Numerous runs were performed for reflection coefficients in the range 0.85 –0.99. The most successful simulation results were achieved with the model of the partial absorber / specular reflector which was implemented using the option “mirror with a possible partial absorption fraction”. The necessary optical data were found in the manufacturer’s catalog [6]. Simulations with 10,000 and 100,000 histories were run in order to achieve statistically valid results with an error less than 1%.

A reflection coefficient, RC, of 0.968 showed the closest fit to the experimental results, which is presented in Figure 8. One of the major limitations of the experiment was that the length of a scintillator slab, 30 cm, was quite short compared with the bulk light attenuation length for a given BC-408 scintillator, 380cm. As has been reported in the literature [15], there is a rapid, non-linear decrease in signal amplitude at short distances from the photomultiplier. The main reason for this is the rapid decrease of the solid angle

of the cone of light viewed directly by the PMT. This limitation could be overcome by using for the measurement a longer scintillator with a length comparable to the bulk attenuation length.

Figure 8. Attenuation by BC-408 slab: Measured vs. Simulated with DETECT II using “smooth” surface finish with the reflection coefficient, $RC=0.968$. Data is normalized to its 7 cm value.

Further, a superior measurement could have been achieved by placing the sources at more positions along the Z-axis of the slab.

The results obtained by the simulation with DETECT II are considered quite accurate and a sound basis for further work. The major limitation of DETECT II is that it can simulate only rectangular solid (‘slab’) geometry. In order to model spherical geometry, the

simulation program DETECT, which allows for the specification of any complex geometry, was used.

3.7 Verification of the Equivalence of *DETECT II* and *DETECT* for Slab Geometries to Justify DETECT for Hemispherical Geometry.

To validate DETECT (specifically, version DETECT97), the same experiment in slab geometry was simulated using the DETECT97 [19] computer program.

Simulation with the POLISH surface type and the same reflection coefficients, RC as in DETECT II results in less attenuation of light. This indicates that some sources of scintillation light loss were omitted from DETECT [32]. In order to better simulate the measured light attenuation, another surface finish option was introduced into the model. This refinement was appropriate because in actual fact, the scintillation bar had both ends cut and machined, as compared with the polished sides. The surface type for the machined end was simulated using the UNIFIED surface finish. In contrast to the POLISH or GROUND surface finishes, the UNIFIED surface finish allows a wide range of surface roughness values, using an α angle between a micro-facet normal and the average surface normal which is assumed to follow a gaussian distribution with a standard deviation of σ_α . Like the other surface finishes, UNIFIED also allows a reflection coefficient, RC, to be specified to simulate an external diffuse reflector. UNIFIED treats this reflection coefficient in the same manner as POLISH and GROUND, with the addition that an index of refraction, can be specified for the reflective coating. With the UNIFIED surface finish and RC=0.965 for one end of the

scintillator bar , and a POLISH surface with $RC=0.965$ for the rest of the slab's surfaces , the simulated results showed the closest fit to the measured ones.

The results of the simulation are presented in Table2 and Figure 9.

Taking into consideration the plausible claim in the literature mentioned above that there is more rapid change in the signal amplitude close to the phototube, the results presented in Figure 9 demonstrate quite consistent behavior. The points, at 12 cm and 18 cm, show more scatter around measured data, while the two last points have a tendency to fall closer to the measured values. A comparison of the simulation results of DETECT II and DETECT (version DETECT97) supports the conclusion that DETECT (version DETECT97) code could be appropriately be used in further investigations into instrument design.

Table 2. Relative light yield, % in BC-408 measured experimentally and calculated using DETECT II and DETECT Monte Carlo simulation programs. Each set is normalized to its 7 cm value.

Distance, cm	Simulated, %, DII	Measured, %	Simulated, %, D97
7	100.0	100.0	100.0
12	94.0	95.9	95.4
18	88.9	89.7	90.9
23	86.1	86.3	86.8
28	84.3	84.4	85.0

***Note:** DII – DETECT II, D97 – DETECT (version DETECT 97)

Figure 9. Relative light attenuation by BC-408 measured by an experiment (Series 2) and simulated using DETECT II (Series 1) and DETECT (Series3) Monte Carlo computer programs. Data normalized to its 7 cm value.

CHAPTER 4. EXPERIMENTS WITH A HEMISPHERE

4.1 The Design of a Detector

This experiment tested a detector design consisting of a single hemispherical layer, which represented one layer of the final multilayer-spherical configuration for the neutron spectrometer. Each layer would serve both as a thermal neutron detector and a lightguide. This is possible, because as a hydrogenous material it moderates neutrons to thermal energies and as a scintillator containing 6-Li it is sensitive to thermal neutrons. Also, as a transparent material it can convey light photons. Spherical shape is needed to preserve an isotropic response (independent on spatial orientation with respect to the radiation source) as in the case with Bonner spheres spectrometer; but the current design optimized the configuration by combining it into a concentric multilayer geometry. This avoided the main pragmatic disadvantage of Bonner spheres spectrometer, namely, that it is bulky and cumbersome [34]. A spherical configuration with concentric layers would be assembled by the manufacturer from possible sections of a sphere, such as hemisphere, half-hemisphere, quarter-hemisphere or smaller divisions. One of the goals of the light transport studies was to determine whether it would be advantageous to divide the hemispherical layers into smaller sections, in order to improve light collection efficiency. Another concern was the dependence (variation) of the light output on the location of scintillation event within the scintillator volume.

4.2 Geometry and Composition of the Detector Prototype

It was originally intended that the model be constructed of a polyvinyltoluene (PVT) based scintillation material loaded with boron. This material is commercially available as

BC-454 scintillator from the Bicon company. During preliminary trials BC-408 scintillator material without boron was employed as a prototype. Later the idea of using BC-454 was abandoned because of its prohibitive price (approximately \$6000 per liter). One layer of the proposed multilayer spectrometer design was finally tested with BC-702 scintillator as a cheaper alternative.

The proposed model for the detector test consisted of a single hemispherical layer of Plexiglas (thickness 10 mm), coated inside with a 1 mm-layer of ZnS(Ag) powder loaded with Li-6. This material is available as the BC-702 scintillator manufactured by Bicon. The properties of this material are described by the manufacturer in the following words [6]:

“The detector incorporates a lithium compound (enriched to 95% Li-6) matrix dispersed in a fine, ZnS(Ag) phosphor powder. The detection process employs the ${}^6\text{Li} (n, \alpha) {}^3\text{H}$ nuclear reaction in which the resulting alpha particle and triton produce scintillation upon interacting with ZnS(Ag)”.

A hemispherical layer of the described composition with an internal diameter of 5” (radius = 64 mm) was designed in order to fit on the top of a 5” diameter Bonner sphere moderator. A cylindrical light guide, 2 cm long and 2 cm in diameter, was inserted on the top of the Plexiglas hemisphere at one end and coupled to the PMT (Type No R1450, tube diameter 19 mm) at the other end using optical grease. The PMT and a light guide were connected inside the cylindrical Plexiglas holder in order to ensure the stability of the joint between them. The entire configuration was then wrapped in several layers of wrinkled aluminum foil (Figure 10).

4.3 Experiments in Neutron and Gamma Radiation Fields

4.3.1 Goal of the Experiments

The goals of the experiments were to evaluate the response (sensitivity) of the proposed detector model to neutron radiation, and to measure its ability to discriminate against a gamma radiation background.

A series of experiments were performed at two different locations at the Stanford Linear Accelerator Center (SLAC):

- 1) "Source Well" in the OHP (Operational Health Physics) building
- 2) Radiation Physics laboratory

4.3.2 "Well Room" Measurements

The "Well Room" in the OHP building was chosen for the first experiment because it has a variety of neutron and gamma sources of different activities which could be used to measure the sensitivity. The encapsulated sources are suspended inside shielded concrete wells on chains and can be brought up closer to the surface at a known distance. This allows the experimenter to test the response of the detector to different amounts of radiation without taking the sources out of the well.

In order to evaluate discrimination between gamma and neutron radiation, a number of measurements of gamma radiation were made. For this purpose two gamma sources of different energy were used: Co-60 (photon energies 1.173 MeV and 1.332MeV),"Right Source Well", activity of 0.066Ci (7/93); and Am-241 (photon energies 59.5KeV, 13.9 KeV, and 26 KeV), activity of 50 mCi. The setup for an experiment with Co-60 is shown

in Figure 10. The neutron source used in the experiment was an Am-Be source having an activity of 50 mCi. Am-241/Be source emits neutrons from ${}^9\text{Be}(\alpha, n){}^{12}\text{C}$ reaction, and the same gammas as for pure Am-241 source. The neutron source was measured both without and with a shielding of 5-mm lead. Lead shielding was used to absorb gamma radiation from the source in order to discriminate between gamma and neutron radiations. It was expected that the other sources located in the room might contribute to the background, and these had to be discriminated from “useful” radiation produced by the radioactive sources. To enable this discrimination background measurements were made separately for the two experimental setups with Co-60 (γ) and Am-Be (n) sources, since they were measured at two different locations.

Before actual measurements with the source, a few measurements were done to set an electronic circuit to accept pulses above electronic noise. It was done by setting the Lower Level Discriminator (LLD) to discriminate what was thought to be not a useful signal. After the LLD was set, the same NOMAD was used for all experiments.

Parameters of the experiments are as follows: High Voltage (HV) – 1000V; Gain – 4; Live Time (Table 3).

The analysis of the measurements in the “Well Room” presented in Table 3 shows that background counts may have contributed about 17% to the counts of the Am-241/Be source with shielding. The background most probably was from the strong gamma sources, and/or from the presence of thermal neutrons leaking from the neutron-source wells.

4.3.3 “Radiation Physics Building” Measurements

In order to avoid a strong and essentially unknown background, another series of measurements was conducted in the Radiation Physics Building. Indeed, the possible background contribution to the Am-Be source measurement is 0.8%, to the counts of the Am-241/Be source with lead shielding

4.3.4 Results

The expected neutron capture peak was not seen in the spectra taken using the experimental detector (Figure 11). Neutron measurements would still be possible if the observed neutron spectrum could distinguish between γ -rays and neutrons by pulse height. To answer this question, the response of the detector to known γ and neutron fields was measured and simulated (Table 3 and following).

Table 3 was constructed using the “Region Of Interest” function of the calculation techniques for spectra available in the program MAESTRO for *Windows 3.n*.

Figure 10. Experimental setup for Co-60 measurements using "Right Source Well"

Table 3. Response of the experimental detector to known neutron and gamma radiation.

Source	SUM [counts]	ROI [channels]	SUM [counts]	Ratio [%]	Live Time [s]
OHP Building, "Well Room"					
Bkgd Co-60	1.5489×10^4	68-180	0.9190×10^4	59	1200
"	"	68-248	1.0824×10^4	70	"
Co-60, 5mR	1.12849×10^5	68-180	0.93309×10^5	83	1200
"	"	68-248	1.00188×10^5	89	"
Am-241	1.7299×10^6	68-180	1.50399×10^6	87	1200
"	"	68-248	1.51891×10^6	88	"
Bkgd for Am-241	1.7035×10^4	68-180	1.1013×10^4	65	1200
"	"	68-248	1.2818×10^4	75.2	"
Am-Be with Pb	9.9740×10^4	68-180	6.3866×10^4	64	1200
"	"	68-248	7.4427×10^4	75	"
Am-Be w/out Pb	1.84650×10^5	68-180	1.41892×10^5	77	1200
"	"	68-247	1.53718×10^5	83	"
Radiation Physics Building					
Bkgd	5.174×10^3	68-180	3.878×10^3	75	1800
"	"	68-248	4.145×10^3	80	"
Am-Be w/out Pb	1.18702×10^7	68-180	1.0694×10^7	90	621
"	"	68-248	1.08289×10^7	91	"
Am-Be with Pb	6.63090×10^5	68-180	4.30445×10^5	65	"
"	"	68-248	499764	75	"

Figure 11. Am-Be neutron source measured with an experimental detector:
a) Without shielding (lower curve), b). With the lead shielding between the source and detector (upper curve).

4.4 Calculation of the Sensitivity of the Experimental Detector-Layer

4.4.1 Sensitivity of the Detector

The sensitivity of a radiation detector may be defined as [7]

$$\text{Sensitivity} = \text{counting rate} / \text{fluence rate} \quad [\text{cnts} \cdot \text{hr}^{-1} / \text{n} \cdot \text{cm}^{-2} \text{hr}^{-1}] \quad (9)$$

In order to evaluate the fluence at the setup location, dose rate measurements were taken at that site with a survey meter. Using the measured dose-rate data or the known activity of the sources, the fluence of photons was calculated. Based on the measured counting rate and calculated fluence values, the sensitivity of the experimental detector was calculated. The results are presented in Table 4.

4.4.2 Fluence Calculation

4.4.2.1 Gamma Radiation

The decay scheme of Co-60 has two gammas of 1.173 and 1.332 MeV. For this calculation an approximately average energy 1.25MeV was used. The fluence-to-dose conversion factors were known for 1 and 1.5 MeV, and the conversion factor for 1.25MeV, $5.51 \times 10^{-10} \text{ rad} \cdot \text{cm}^2$, was obtained by interpolation. The fluence can be calculated from the dose rate

$$D[\text{rad/hr}] = C[\text{rad} \cdot \text{cm}^2] \times \phi \text{ cm}^{-2}, \quad (10)$$

Where $C [\text{rad} \cdot \text{cm}^2]$ is the fluence-to-dose conversion factor, $D \text{ rad/hr}$, is the dose, and $\phi \text{ cm}^{-2}$ is the fluence. Hence $\phi [\text{cm}^{-2}] = D/C$. Using the measured dose rate for Co-60, 1.35 mrem/hr , the fluence rate for gamma radiation was calculated to be $2.45 \times 10^6 \text{ cm}^{-2} \text{hr}^{-1}$ at the top of the open well. Sensitivity was calculated as the ratio of the measured counting rate to calculated fluence rate.

Table 4. Calculated sensitivity of the detector under study to gamma radiation.

Source and Location	Dose rate measured mrem·hr ⁻¹ (cnts·hr ⁻¹)	Fluence rate calculated cm ⁻² hr ⁻¹	Sensitivity cnts·hr ⁻¹ /n· cm ⁻² hr ⁻¹
Co-60 at the Bottom of the well	1.35 (1.5489x10 ⁴)	2.45x10 ⁶	0.8x10 ⁻²
Co-60 Brought “up” at the fixed dose rate	5 (1.12849x10 ⁵)	9.07441x10 ⁶	1.2x10 ⁻²
Am-241	6.63090x10 ⁵	3.90650x10 ⁸	1.69x10 ⁻³

4.4.2.2 Neutron Radiation

The neutron sensitivity was also calculated, using Equation 9 and information about the Am-241/Be source’s emission rate, which is 1.1×10^5 n/sec at 1 m from the source [Certificate from OHP]. The counting rate for neutron radiation was taken from the experiment in the Radiation Physics Building, since the “Well Room”, in the OHP building seemed to have significant background contribution from the numerous sources of gamma and thermal neutron radiation located in the room.

Table 5. Calculated sensitivity of the detector under study to neutron radiation.

Source and Location	Measured cnts·hr ⁻¹	Calculated Fluence Rate cm ⁻² hr ⁻¹	Sensitivity Cnts·hr ⁻¹ /n· cm ⁻² hr ⁻¹
RP Bldg.	3.9575x10 ⁴	3.1513x10 ⁵	1.25x10 ⁻¹
“Well Room”	5.2483x10	3.1513x10 ⁵	1.6762x10 ⁻⁴

4.5 Analysis of the Experiments in the Neutron and Gamma Radiation Fields

One of the critical issues of a detector design as a spectrometer for neutron field measurements depends, among other aspects, on the ability to discriminate the neutron signal from photons and other background. In thermal neutron detectors this is usually possible thanks to the presence of a distinct “neutron capture peak” in the pulse-height spectrum.

4.5.1 Neutron Capture Peak

Spectra taken from the Am-Be source did not exhibit a distinctive peak from neutron capture reaction (Figure 11) . An example of how the neutron peak from the capture reaction should appear after the measurements is shown in Figure 12. However, it should be noted that the data of Figure 12 were obtained with a clear (transparent) boron-loaded scintillator,

Figure 12. Thermal neutron capture scintillators.

while the present experimental measurements were performed using an opaque scintillator, ZnS(Li).

The absence of the distinctive neutron capture peak could be explained by the optical transport spreading and degrading the neutron pulse. According to the manufacturer, a thickness greater than about $25\mu\text{g}/\text{cm}^2$ becomes unusable because of the opacity of the multicrystalline layer to its own luminescence [6]. This makes obvious the fact that only the layer bordering upon the Plexiglas lightguide emits light photons into the lightguide. Furthermore, scintillation photons emerging from deeper layers are partially or totally diffused and absorbed within the highly attenuating opaque ZnS/LiF layer, depending on the depth of the scintillation event. The amount of collected light will therefore vary greatly from event to event, resulting in a continuum rather than a distinct peak in the pulse-height spectrum.

4.5.2 Discrimination between Gamma and Neutron Radiation

A further attempt to identify the population of the measured spectra demonstrated a very weak possibility of discrimination between neutron and gamma radiation. Thus, the results presented in Table 3 show that neutrons populate the middle part of the PHA spectrum, while gammas populate the lower one.

The measured sensitivity to both gamma and neutrons provides some quantitative information on discrimination between these radiations.

Thus, sensitivity to gammas (Table 3) is on the order of 10^{-2} or 10^{-3} , depending on the energy of the radiation. This is obviously a non-negligible amount, which makes a sure discrimination between gamma and neutrons difficult. Although the detector-scintillator ZnS(Ag)/LiF was characterized by its manufacturer as having very little sensitivity to gamma radiation, certain other factors might contribute to it, generating additional light:

- 1) Interaction of the low energy gamma radiation from Am-241 source with the relatively high Z scintillation material (ZnS(Ag) incorporated with Li⁶) by the photoelectric effect (PE).
- 2) Generation of Cherenkov radiation by fast electrons in the Plexiglas irradiated in the Co-60 source field.

The calculated sensitivities to neutrons cannot be compared for the measurements taken in the “Well Room” (1.6762×10^{-4} cts·hr⁻¹/n·cm⁻²·hr⁻¹) and those taken in the RP Building (1.25×10^{-1} cts·hr⁻¹/n·cm⁻²·hr⁻¹), as shown in Tables 4 and 5, since the distance from the detector to the source was not calibrated. However, the following factors could be taken into account:

- 1) High background radiation (Table 3) from the Co-60 gamma sources located very close to the experimental detector. (The detector was placed against the “Right well source” wall to direct radiation from the tested sources into the wall, while performing measurements.) The gamma ray background radiation emitted from the Am-241 source consisted mainly of three gammas: 59.5 KeV (36%), 13.9 KeV (42.7%), and 26 KeV (21.3%), of which most probably only the first one could contribute to the background.

- 2) It is known from the literature [1] that neutrons emitted from Am-241/Be source have average energies of $\cong 4$ MeV. Neutrons of this energy would most likely require additional moderating by polyethylene (PE) to thermal energies.

A higher degree of neutron moderation was achieved in the “Radiation Physics Building” experiment. In this case the detector was surrounded by additional blocks of polyethylene (PE) inside the black box containing the detector.

4.6 Light Collection Uniformity Evaluated with a Light Emitting Diode

4.6.1 Goal of the Experiment

Light transport in the proposed detector was studied by conducting an experiment with a pulsed green Light Emitting Diode (LED). The goal of this experiment was to evaluate the uniformity of light collection, that is, the dependence of the light output on the distance from the scintillation source to the PMT.

4.6.2 Description of the Experiment

A pulsed LED is a convenient source of light which also makes possible an emulation of the “Point Source” mode in the light transport simulated with the DETECT computer program. The wavelength of maximum emission for BC-702 is 450nm. This is close to the green part of the visible light spectrum. For this reason a green LED was employed in the experiment. An LED was placed in a short cylindrical metal holder, which was itself secured in another stiff foam holder. This allowed moving the LED along the side

of a Plexiglas hemispherical layer, and placing it at a known distance from the PMT, without fastening it directly to the surface of the lightguide.

Figure 13. The light output peak received with the green LED.

Figure 14. Experimental setup for conducting the "LED experiment".

The whole configuration was covered with wrinkled aluminum foil, leaving a slit opening for a paper scale (geometrically an arc), which was attached to the hemispherical surface. A number of measurements were carried out, placing the LED each time at a different location on the external surface of the Plexiglas hemisphere, along the paper scale. Nine measurements were performed, starting at 1cm above the bottom of the hemisphere, with an increment of 1 cm for each successive location. This technique helped to ensure reproducibility of the positioning of the LED, despite the curved surface of the hemispherical layer. The light output peak and an experimental setup are shown in Figures 13 and 14 respectively.

The measurements were repeated twice: a) without aluminum foil covering the slit-scale; and, b) with the aluminum foil, confirming a fairly good reproducibility of the results demonstrated in Table 6 and Figure 15.

These results were used for the validation of the simulation tests with DETECT presented in Chapter 5.

Table 6. Attenuation by a Plexiglas hemisphere: a) Without aluminum foil, covering the slit-scale, b) With a completely covered a slit-scale by aluminum foil

Distance, cm From PMT	Channel # a) Without aluminum foil	Ln (Channel #)	Channel # b) With aluminum foil	Ln (Channel #)
3	811	6.69	796	6.68
4	443	6.09	408	6.24
5	268	5.59	284	5.65
6	212	5.36	200	5.30
7	150	5.01	153	5.03
8	145	4.97	145	4.98
9	144	4.97	143	4.96

Note: The first two measurements at 1 and 2cm from the bottom of the hemisphere were disregarded because of the very low light output.

Figure 15. Experiment: Attenuation by a Hemisphere measured with a LED.

Series 1: (a) Without full coverage with Al foil (scale-slit was open).

Series 2: (b) Fully covered with Al foil.

CHAPTER 5. OPTICAL MODELING WITH SPHERICAL CONFIGURATIONS

5.1 Goals of Light Transport Modeling.

The light transport study presented in this Chapter pursued the following goals:

1. To reproduce the results of the “LED experiment” described in the preceding chapter for a hemisphere, thereby determining the optical parameters (surface finish and reflection coefficient).
2. Using the optical parameters thus determined for further investigation, to find an optimal geometrical configuration for a detector made of the BC-702 scintillation material.

5.2 Aspects of the Light Transport Investigation

The proposed geometrical configurations, designated as hemisphere, half-hemisphere- and quarter-hemisphere (Figure 20) were implemented and tested using the program DETECT [31] to study the following aspects of light transport:

1. Light yield as a function of position of the source;
2. Influence of the above on uniformity of light collection (Pulse Height Distribution);
3. Other variables affecting light output in a layer of a modeled spectrometer:
 - The shape of the detector layer, such as hemisphere, half-hemisphere and quarter-hemisphere;
 - The simulated surface finish of the interfaces; and
 - The reflection coefficient, RC, for non-perfect interfaces.

This study was performed by simulating the cumulative effect of all rays emitted from a single point source or a distributed source inside the scintillator. Light transport simulations for the alternative design (half-hemisphere- and quarter-hemisphere) were conducted in the Plexiglas layer only.

The first part of the study was devoted to demonstrating good agreement between the simulations with DETECT and the experimental measurements. This was executed according to the following scheme:

- simulation of the proposed model of a detector
- experimental testing of the same model of the detector
- validation of simulations against experiment and selection of appropriate parameter values

5.3 Simulation Details.

5.3.1 Simulated Detector Model

The first simulated detector (with the program DETECT) modeled the experimental prototype described in Chapter 4. It was represented as a hemispherical layer with a radius of 2.5" (64 mm) in order to fit on the top of the 5" diameter Bonner sphere moderator ("spherical" geometry in DETECT is described in terms of the radius of the sphere). The internal surface of a shell was modeled as a layer of an inorganic scintillator ZnS (Ag), simulated as surface finish "PAINT", whose optical properties are given by [6]; with a radius of 64 mm and a thickness of 1 mm. This layer was followed

by 1 cm of Plexiglas [18] coated with the layer of reflective material, which was simulated as a metal coating (surface finish “METAL”). A cylindrical light guide, 2 cm long, and 2 cm diameter, was inserted on the top of the hemisphere (Figure 16). The top of the cylinder was represented as a PMT window with a detecting layer (surface finish “DETECT”) on the inside. Reflection coefficients were used to model the reflection properties of both the inorganic scintillator layer and the wrinkled aluminum foil in which the scintillator was wrapped. Since an independent measurement of this quantity (RC) is not available, its value was found by comparing the experimental data with the simulation results (described in Case #1, below).

5.3.2 Light Source

Earlier versions of the program DETECT do not simulate the energy deposition by charged particles passing through the scintillator and the conversion of the deposited energy to light. Thus the function which generates photons in DETECT was modified by the current investigator in order to specify the number of photons generated from a single scintillation event. Together with the number of runs, which is specified in the configuration file for DETECT, these input parameters allow the analyst to generate any number of photons per event in the scintillation material. In order to estimate the number of light photons generated from a single scintillation event for the materials tested in the simulation, the following assumptions were made:

- The number of photons is proportional to energy deposited by the incident particle in the scintillator;
- Fluctuations in the deposited energy were not considered.

For ZnS(Ag) scintillator, no direct data were available, and an estimated approximation was made as to the total light yield of ZnS(Ag) relative to that of NaI (TI) by consulting the literature [16]. 100 photons per event was considered reasonable by this estimate, and running 10,000 events, gave as a total 1,000,000 transported photons, with the typical uncertainty on scored photons below 1.0%.

5.3.3 Light Sources Used in the Simulations

Photons can be generated in DETECT using two modes (Chapter 2):

- 1) “Point source”: the model assumes that scintillation events occur at a certain specific point inside the scintillator. This mode was used to simulate the “LED experiment” of the previous chapter.
- 2) “Volume (distributed) source”: scintillation events are uniformly distributed within the volume of the scintillator.

Both above modes were used to simulate and study alternative geometries of the detector.

5.4 Comparison of the Simulations Against the Experiments as a Validation for Further Research

5.4.1 Simulation of the LED experiment

The LED experiment (described in Chapter 4) was simulated in order to compare the results produced by DETECT with the experimental measurements. The results of the simulation could at the same time be used to investigate the dependence of the light output on the location of the scintillation events in the detector.

Figure 16. Detector model.

In order to study the dependence of the light yield on the particular location of the scintillation events, as was done in the “LED experiment”, a single point source was simulated in 7 different locations along a circumferential line passing through the PMT. The first point source was located at 1 cm above the bottom of the hemisphere, with an increment of 1 cm for every successive location. (The locations at 1 and 2 cm were disregarded because of the low light output demonstrated by the experiment.) The detector, which served as a prototype for simulations, is shown in Figure 16, and its simulated model is described in section 5.3.1. The LED used in the experiment was simulated as a “Point source”, since in the experiment it was placed as a small, localized source on the external surface of the hemisphere along a scale which was attached to this surface. The LED itself was placed in a small metal cylinder in order to ensure the reproducibility of its positioning (described in Chapter 4).

To reproduce the conditions of the experiment a set of point sources was simulated—not inside the ZnS scintillator, but rather on the outer surface of the Plexiglas hemisphere. The external surface of the hemisphere was simulated as “METAL” coating with adjustable reflection coefficient, in order to simulate loosely fitted wrinkled aluminum foil.

Since the LED was confined in a metal cylinder (constraining the emission solid angle), two different approximations were tried in the simulation. The first one was isotropic generation of light from a point source, while the second model introduced light generated isotropically within a specified cone. In the experiment the cylinder with the LED was attached perpendicularly to the curved surface of a hemisphere. Therefore, in the simulation the axis of the solid angle was directed toward the center of the sphere.

Attachment of the LED was made using optical grease with a matching index of refraction, and this interface was properly represented in the simulation. For validation of the experimental results seven point sources, starting from 3 cm along the hemisphere's arc surface, were simulated. The coordinates (X, Y, Z,) were calculated using Equation (11) for the arc length:

Figure 17. The hemisphere used in the “LEDexperiment”. The open slit in the middle is where the LED was placed, starting from the bottom of the hemisphere and moving up with an increment of 1 cm.

$$D = \alpha * R \quad (11)$$

where α is an angle of arc in radians, R is the radius of the hemisphere and D is the distance from the bottom of the hemisphere to the location of the point source (a paper scale was fixed to the surface of the Plexiglas hemisphere). The α value was calculated using Equation 11 (in radians, and converted to degrees). The X coordinate was

calculated as $R \cdot \cos \alpha$, assuming the Y coordinate was equal “0”). Finally, the Z coordinate was calculated as $Z = (R^2 - X^2)^{1/2}$. The X, Y, and Z coordinates were used as the input parameters for the source location in the simulations.

The results of the simulation are presented in Figure 18.

Figure 18. Attenuation by a Hemisphere: Measured – Series 1, Simulated with an isotropic source – Series2, Simulated within a cone of 30 degrees – Series 3. Data normalized to its 7 cm value.

It can be seen from Figure 18 that the measured and simulated results are in quite good agreement (for the isotropic mode within 4-6%; for a directed one within 3- 4%).

However, the “isotropic source” (Series 2) simulation points fall further away from the measured points than those simulated within a cone at a longer distances from the PMT.

It would appear that in this particular case, the LED is better described by a distribution within a specified cone, undoubtedly due to the use of a metallic collimator in the experiment. Some discrepancies between the experimental and the simulated data might be attributed to the limitations of DETECT presented in section 5.4.2.

The results in Figure 18 were achieved with the parameters which were chosen on the basis of theory (Chapter 1), consulting literature [2,3,6,15], and the comparison between experiment and simulation. These values are as follows:

- ZnS surface described as “PAINT” with RC (reflection coefficient) of 0.90.
- Plexiglas surface was simulated as a “POLISH” case with an external coating of “METAL”, RC=0.965.
- Light photon generation was performed in two modes: 1) an isotropic mode; and 2) an isotropic mode, within a cone of 30 degrees. One million photons were generated in each run, resulting in a statistical uncertainty on the final tally, based on the number of collected photons, of less than 1%.

Numerous runs were made with different RC values but those presented here show the closest fit.

5.4.2. Limitations of the Simulation with DETECT.

Some conditions of the experiment were not reproducible by the simulation because of limitations of DETECT. This may have contributed to certain discrepancies between the simulated and experimental results.

One experimental condition, difficult to model, was that the LED was placed at a certain point along an open (uncovered by aluminum foil) slit and after that the whole construction was wrapped loosely in wrinkled aluminum foil, overlapping the slit. It was not possible to simulate this exact situation with DETECT. In the simulation, the scintillation point source (the LED) was placed on the polished surface of the Plexiglas layer, and the outer surface of the configuration was simulated as coated with metal

(surface finish “METAL”), with a reflection coefficient matching the wrinkled aluminum foil in the experiment. It was not possible in this particular case to simulate the metal coating as the outer surface-envelope for the whole complex geometry. The hemispherical layer and the cylindrical light guide had their outer surfaces simulated as the same metal coating, but they represented different components with disparate areas of contact.

Another limitation was that DETECT allows for light to escape through incompletely overlapped regions of contact between components [31]. With this approximation some light loss mechanism was introduced in the simulation and “Escaped” photons were reported.

Yet another factor of discrepancy was introduced by the non-uniformly wrinkled aluminum foil, which might result in patched reflectivity (Chapter 1) for different areas of the hemisphere. This condition was also not possible to simulate with DETECT.

A final difficulty in the simulation was the representation of the inner surface of the detector, which actually made of ZnS(Ag) pressed powder coated on the plexiglas layer. The most accurate way to describe such a surface was by the “PAINT” case with an adjustable reflection coefficient, which would simulate diffuse reflection/partial absorption. The simulation assumes this coefficient is well known, but in fact there was no data available in the literature on this case at the time of simulation. For this reason some discrepancies could be expected in the approximation of the optical properties of the internal layer.

In spite of the limitations of DETECT, the results of the simulation showed a good agreement with the experimental ones, as set forth by the data presented in Figure 18. On the basis of this agreement, our current modified version of the program DETECT was expected to be a valid tool in the prediction of light transport for the instrument's alternative geometries.

5.5 Geometry Optimization

As was mentioned above, the ultimate goal of this investigation was to define the optimal design of an instrument which would ensure reasonably uniform light distribution (attenuation of a signal depending on origin) with a good light output (efficiency). The light yield and uniformity affect the energy resolution of the scintillators and limit the performance of the large scintillators.

5.5.1 Geometrical Configurations Simulated

The geometrical configurations of a hemisphere, and its sections, such as half-hemisphere and quarter-hemisphere (Figure 20) have been simulated and analyzed. The alternative geometries of half- and a quarter-hemisphere were modeled by cutting the hemisphere along X axis and, X and Y axes respectively.

The issues investigated with above geometries are described in sections 5.5.2 –5.5.4 with a summary in 5.6.

5.5.2 Efficiency of a Particular Geometrical Configuration of a Detector.

The definition of the efficiency is the ratio of the “number of pulses recorded” to the “number of quanta emitted by the source”. The program DETECT calculates the efficiency of the detector as the number (and percentage) of the light photons reaching the detector surface divided by the total number photons of generated by the point source. When different geometries are tested, they yield a different probability for a photon to reach a detector in that configuration.

5.5.3 Pulse Height Distribution

Another important piece of information is the pulse amplitude as a function of the location of the scintillation event, i.e. the pulse height distribution throughout the volume of the detector. The dependence of the light yield on the location of the scintillation events measures the uniformity of light collection.

The program DETECT was modified by the current investigator in order to display the pulse height frequency distribution. A histogram distribution is generated which bins the number of detected photons from a simulated scintillation event of 100 photons on the X axis, against the number of such events on the Y axis. The maximum pulse size was defined as an ideal case of 100 photons generated in a single scintillation event which reach the detector. The bin size was one photon.

Both features, efficiency and pulse height distribution, were investigated using the “Point source” and “Volume source” generation functions, for all three geometrical configurations.

1.Hemisphere

2. Half hemisphere

3. Quarter hemisphere

Figure 19. Hemisphere and alternative geometries.

5.5.4 Main Input Parameters

The main input parameters which describe geometry and optical properties used in the simulations are presented in Table 7.

Table 7. The main input parameters used for all simulation cases.

Parameter	Input Value
ZnS refraction index	2.36
Plexiglas refraction index	1.49
Plexiglas absorption length	7600mm
Radius of the sphere (internal)	64mm
ZnS layer thickness	1mm
Plexiglas layer thickness	10mm

5.5.5 Variable Input Parameters.

The effects of some factors on the light output and a pulse size for a simulated detector were investigated in this study, namely:

- Surface finish
- Reflection coefficient, RC
- Geometrical configuration

A number of cases are presented in the next section, in order to demonstrate the methodology of the simulation in detail.

5.5.6 Simulation Cases Studies

Case Study #1.

Case #1 presents the parameters that gave the closest simulated fit to the “LED experiment” for a hemispherical geometry (Figure 18). Simulations with the same parameters were run for a half-hemisphere, and for a quarter-hemisphere in order to examine the dependence of the light output on the geometrical configuration. (A section of the “Simulation Report” of the output files is presented in the Appendix.) In order to have a fair comparison in the absolute sense, the histograms for all three configurations are based on the same number of scintillation events, namely 1,000,000.

Input parameters:

1. Light photons generated from the point sources located at 3 cm and 9 cm from the bottom of the configuration.
2. An external layer simulated as the surface finish “METAL”, $RC = 0.965$.
3. An internal layer simulated with the surface finish “PAINT”, $RC = 0.90$.

Table 8 lists measured (Series 1) and simulated data for a “Point Source” with an isotropic distribution (Series 2) for a hemisphere (Figure 18). These data were compared with the simulated data for a half-hemisphere and a quarter-hemisphere. Table 9 is presented here to demonstrate a relative attenuation of the light output depending on the location of the scintillation event for all three configurations. The simulations for two locations, 3cm and 9cm from the bottom of the configurations, were run for a “Point

Source” with an isotropic distribution of generated photons. The ratio of the light output at the top to that of the bottom for all three geometrical configurations was calculated.

Analysis of Results

In order to choose an optimal geometrical configuration the data from Tables 8 and 9 have been analyzed.

Results from Table 9 demonstrate that the difference in the light output at 3 cm between the hemisphere and a half-hemisphere is quite significant: 0.46% vs 0.38%. This means ~17% drop in efficiency, calculated as $(1-0.38/0.46)*100$. Table 9 shows that the hemisphere is better both at absolute light collection and (lower) variation of the light output. Analysis of data from Appendix 1, which presents a “Simulation Report”, shows that there is some difference in “Dielectric Surface Interaction” (DSI) events for all three configurations, which gives a difference in “Surface Absorbed” photons. Most significantly, a hemisphere has a smaller percentage of Fresnel Reflection (FR) events, in which photons are absorbed at the surface interface because the RC less than 1.0. In the case in which a reflection coefficient is specified for the outer-layer coating, the transmitted photon may be returned back to the original medium with a Lambertian distribution, which allows more variety of angles of reflection. (In the case of Lambertian distribution, the angle of reflection is independent of the angle of incidence.)

The last column “Ratio top/bottom” in Table 9 demonstrates the loss of the light output at the top of the configuration to that at the bottom. In the simulations for three geometrical configurations, the ratio “top/bottom” varied from 4.9 (hemisphere) to 5.4 (quarter-

hemisphere) for 10^6 histories. The hemisphere demonstrates a smaller ratio. This fact could most likely be explained by the fact that from a typical point source to the PMT at the top, the path of an average photon will be longer for the hemisphere than for the half- or quarter-hemisphere.

Table 8. Measured (Series 1) and Simulated (Series 2) for a Hemisphere: “Point Source” with an isotropic distribution) data presented in Figure 18. (Total of 50,000 photons generated)

Distance, cm from PMT	Channel # Measured	Counts Simulated	Counts, %
3	796	1107	2.21
4	408	672	
6	200	385	
7	153	312	
8	145	280	
9	143	259	0.52
			Count Ratio
			Top/bottom 4.25±0.07

Table 9. The simulated light output from the point sources for the hemisphere, half-hemisphere- and quarter-hemisphere; internal layer: “PAINT” 0.90 RC and, external layer “METAL”, 0.965RC. (Measurement starts at the bottom of the configuration). Total number of 1,000,000photons generated.

Configuration	Photons counted	%	Location, cm	Ratio top/bottom
Hemisphere 1,000,000	4587	0.46	3	4.9±0.02
	22362	2.24	9	
Half-Hemisphere	3798	0.38	3	5.2±0.02
	19608	1.96	9	
Quarter-Hemisphere	3316	0.33	3	5.4±0.02
	17988	1.8	9	

The pulse height distribution histogram in Figure 20, (a) demonstrates a quite distinctive and narrow peak for a source located at the bottom of all configurations. Light photons are attenuated while being transported to the detector by surface (if RC is specified) and bulk absorption. Most detection events occur with the very small number of photons detected per a scintillation event, recording pulses at the “lower channels”. The pulse height spectrum for a “Point Source” at the short distance to the PMT (Figure 20, b) shows a peak shift to the higher channels, as was confirmed by the LED experiment. This tendency is the same for all three configurations. Light output from the “Volume” source, simulated c is shown in Figure 21.

Case Study #2.

Case #2 simulated light output from the “Volume” (distributed) source with the same surface simulation parameters as in Case 1 (Figure 21), and for an “ideal” case (Figure 22).

Input parameters:

1. An external layer simulated as the surface finish “METAL”, $RC = 1$
2. An internal layer simulated with the surface finish “PAINT”, $RC = 1$

Case #2 attempted to determine how light output depends on RC, for RC near 1.0. The simulation was constructed as follows: an internal layer, ZnS(Ag), a diffuse reflector; an external layer a specular reflector –aluminum foil; with no absorption at the surfaces for both layers. The histograms for Case #2 and the following cases are based on 100,000 scintillation events.

Figures 21 and 22 demonstrate that with decreasing reflection coefficient (simulating surface imperfections) fewer photons are delivered per single generation event (shift to the lower channels). The average # of photons per event is somewhere near 2 or 3 for lower RC (Figure 21) and about 24 photons (on average) per event for all RCs=1, (Figure 22). For a better quality reflective surface more photons per event reach the detector. The total light amount collected is the integral of count # multiplied by channel #, summed for all the peak. Figure 22 demonstrates that the counts for larger events are distributed (spread) among a greater number of channels. The difference in total light collected is in favor of the “perfect” RCs.

Hemisphere:

a)

b)

Half-hemisphere:

a)

b)

Quarter-hemisphere:

a)

b)

Figure 20. Case #1: simulated as the “Point Source”, with an isotropic distribution.

An external layer simulated as the surface finish METAL, RC = 0.965.

An internal layer simulated with the surface finish “PAINT”, RC = 0.90.

a). Source located at 3 cm from the bottom, b). Source located at 9 cm from the bottom

Figure 21 . Case #1: “Volume source”: internal layer “PAINT”, RC=0.90; external layer “METAL”, RC=0.965. a) Hemisphere, b) Half-hemisphere, c). Quarter-hemisphere

Figure 22. Case #2: “Volume source”: internal layer “PAINT”, RC=1; external layer “METAL”, RC=1; a). Hemisphere, b). Half-hemisphere, c). Quarter-hemisphere.

Until this point the simulation used two different surface finishes for the internal and external layers, “PAINT” and “METAL” respectively. However, initially, in order to determine the most effective surface finish for the external layer of the detector, two possible surface finishes were proposed for testing: metal or reflective paint coating. With this goal a model was created having both layers of the detector simulated with metal or reflective paint surface finishes: Cases 3, 4, 5, and 6.

Both layers, internal and external, of the geometrical configuration had the following parameters:

Case 3: “METAL”, $RC = 0.94$

Case 4: “METAL”, $RC = 1.0$

Case 5: “PAINT”, $RC = 0.94$

Case 6: “PAINT”, $RC = 1.0$

Case Study #3:

This was a study of the light output when both (internal and external) layers are “METAL”.

Input parameters:

1. Light photons generated from the point sources located at 3 cm and 9 cm from the bottom of the configuration.
 2. External and internal layers simulated as the surface finish “METAL”, $RC = 0.94$
- Reflection coefficient $RC = 0.94$ was chosen to simulate a lower quality specular reflective coating. In reality such a surface might have a non-uniform reflectivity caused by local defects such as scratches, spots etc. (see Chapter1). The upper limit of the

reflection coefficient is the “ideal surface”, $RC = 1$. In reality such a surface does not exist, this case is simulated to indicate possible range of the light output.

Case Study #4:

1. External and internal layers simulated as the surface finish “METAL”,
 $RC = 1.0$

$RC=1$, was chosen to simulate an “ideal” reflective surface properties for comparison with those, which are closer to the real one. The pulse height histograms (Figure 24) show a larger light output and more spread in the spectra, since the collection of light is improved by not having surface absorption.

Results for Cases #3 and #4:

From comparison of the results in Tables 10 and 11, one can see that the metal coating behaves the same as observed for Case # 1. The closer the reflection coefficient is to the “ideal” ($RC=1$), the more photons are collected at the “lower” (from the bottom of the hemisphere) location, giving the larger light output and the reduction of the ratio of the signal from top to bottom (Ratio t/b). The value of the ratio top/bottom, 3.15 (Table 10) and 2.54 (Table 11) is smaller when compared with 4.25 (Table 8) obtained in the LED experiment simulation (Case #1). This is most likely because the collection of light is more efficient when both internal and external layers are specular reflectors with RC closer to “ideal” ($RC=1$). It is also demonstrated by the pulse height histograms for the “Point Source” mode, Figures 23 and 24.

Table 10 . Case #3. Both layers (internal and external) are “METAL”, RC=0.94

Geometry	Counts	%	Location	Ratio: top/bottom
Hemisphere	729	0.73	3	3.15± 0.04
	2297	2.3	9	
Half-Hemisphere	640	0.64	3	3.45±0.05
	2210	2.21	9	
Quarter-Hemisphere	580	0.58	3	3.52±0.05
	2040	2.04	9	

Table 11. Case #4. Both layers (internal and external) are “METAL”, RC=1.

Geometry	Counts	%	Location	Ratio: top/bottom
Hemisphere 100,000	3626	3.63	3	2.54±0.02
	9213	9.21	9	
Half-Hemisphere	3620	3.62	3	2.52±0.02
	9132	9.13	9	
Quarter-Hemisphere	3744	3.74	3	2.38±0.02
	8912	8.91	9

Hemisphere: a)

b)

Half-Hemisphere: a)

b)

Quarter-Hemisphere: a)

b)

Figure 23. Case #3. Both layers (internal and external) are "METAL", $RC=0.94$.
a). Source located at 30 cm from the bottom, b). Source located at 90 cm from the bottom.

Hemisphere:

a)

b)

Half-Hemisphere:

a)

b)

Quarter-Hemisphere:

a)

b)

Figure 24. Case #4. Both layers (internal and external) are “METAL”, RC=1.
a). Source located at 30 cm from the bottom, b). Source located at 90 cm from the bottom.

Case Study #5 and 6: “Volume sources” simulated with coating “METAL”

“Volume” sources were chosen again to simulate a scintillation process in a volume of scintillator.

Case #5: RC=0.97 Case #6: RC=1

RC=0.97 was chosen to simulate a surface with fairly good reflective conditions in reality. Indeed, the pulse height histograms (Figures 26) demonstrate quite narrow and distinctive peaks in the pulse height spectra with the peak shift to the lower-middle channels. RC=1, was chosen again to simulate an “ideal” reflective surface properties for comparison with the properties of the real surface. There is no dramatic difference in the light output for all three configurations in both Cases (RC=0.97 and RC=1).

Hemisphere:

Half-Hemisphere

Eighth volume

Figure 25. Volume source: both layers are “METAL”, RC=0.97

Hemisphere: both “METAL”

Half-Hemisphere

Eighth volume

Figure 26. “Volume source’: both layers are “METAL”, RC=1

Case Studies #7 and #8:

Study of the Light Output When Both (Internal and External) Layers Are “PAINT”

A similar modeling was carried out having both layers of the detector simulated with the “reflective” paint surface finishes for both layers presented in Figures 28 and 29, and Tables 12 and 13. Results of the simulation with RC=0.94 do not differ significantly from the Case METAL (RC=0.94). Thus, for a hemisphere, light output for 3 cm from the bottom of the hemisphere is 0.64 %, compared to 0.73% for METAL (RC=0.94, Table 10). The ratio top/bottom is slightly higher for a painted surface (3.93) compared to that for a metalized coating (3.15). However there is a dramatic difference for an “ideal” case in the light output. Thus, a painted reflector gives a 28.81% of light yield, while a metalized reflector yields only 3.63% (Table 11) at 3 cm from the bottom of the configuration. The ratio top/bottom also favors a painted surface, having a value of 1.08 for a hemisphere, compared to 2.54 for METAL.

Table 12. Case #7 Both layers (internal and external) are "PAINT", RC = 0.94

Geometry	Counts	%	Location	Ratio:top/bottom
Hemisphere				
100,000	640	0.64	3	3.93±0.04
	2515	2.52	9	
Half-hemisphere	380	0.38	3	3.63±0.05
	1376	1.38	9	
Quarter-Hemisphere	252	0.25	3	4.76±0.06
	1188	1.19	9	

Table 13. Case #8. Both layers (internal and external) are "PAINT"

Geometry	Cnts	%	Location	Ratio:top/bottom
Hemisphere				
100,000	28818	28.81	3	1.08±0.008
	31243	31.24	9	
Half-hemisphere	26544	26.54	3	1.06±0.009
	28090	28.09	9	
Quarter-Hemisphere	23496	23.5	3	1.20±0.009
	28090	28.09	9

Hemisphere: a)

b)

Half-Hemisphere: a)

b)

Quarter-Hemisphere:

a)

b)

Figure 27. Case #7: Both layers (internal and external) are "PAINT", RC = 0.94
a) 30 cm from the bottom, b) 90 cm from the bottom

Hemisphere:

a)

b)

Half-Hemisphere:

a)

b)

Quarter-Hemisphere:

a)

b)

Figure 28. Case #8: Both layers (internal and external) are “PAINT”, RC=1

Case Study #9.

Case Study #9 examined light output dependence on the reflection coefficient of the external layer ("METAL") in the three geometrical configurations.

1. External layer – "METAL" with RC in the range from 0.94 to 1.
2. Internal layer - "PAINT", with RC = 0.90

This study was conducted to determine the dependence of the light output on the reflection coefficient of the external metal coating, for different geometries. This was done by varying the value of the reflection coefficient across a wide range (from 0.94 to 1.0). The results in Figure 30 show that the tendency of the light output increases as the reflection coefficient increases for all three geometries. This behavior is quite consistent with the fact that the bulk absorption length for Plexiglas is high (7600 mm), while the surface absorption decreases with increasing RC.

Case Study #10

In Case Study # 10 the values were as follows:

1. External layer – "METAL" with the reflection coefficient in the range from 0.94 to 1.
2. Internal layer – reflector with the reflection coefficients RC=0.80 and 0.90

Figure 29. Light output dependence on reflection coefficients for three configurations: hemisphere (Series 1); half-hemisphere (Series 2); and quarter-hemisphere (Series 3). Internal layer simulated as a diffuse reflector: “PAINT”, $RC = 0.90$. External layer simulated as a specular reflector: “METAL”, RC ranges from 0.94 to 1.

Another simulation was done to study the dependence of the light output on the reflection coefficient of the external layer, with the internal layer a diffuse reflector surface finish “PAINT” with $RC = 0.80$. This study was conducted with the same idea in mind: to demonstrate the dependence of the light output on the reflection coefficient, but with the internal coating being a diffuse reflector. This also was done by varying the value of the external reflection coefficient in a range (from 0.94 to 1.0) in order to demonstrate the variation.

Figure 30. Light output dependence on the reflection coefficient for the hemisphere, internal layer simulated as a diffuse reflector. Series 1: RC=0.90; Series 2: RC=0.80 external layer simulated as “METAL” with the reflection coefficients in the range from 0.94 to 1.

The results of this study show the higher light output for RC = 0.90. It also demonstrates that both cases (“PAINT”, RC=0.90, and RC= 0.80) have lower light output for the reflection coefficient, RC = 0.94 for a “METAL” coating as an external layer. This is because of the large fraction of photons absorbed at the surfaces of both layers, internal and external surface.

CHAPTER 6. CONCLUSIONS

The physical experiments and computer simulations conducted in this study led to several significant conclusions. These conclusions are presented below.

At the inception of the investigation, the experimentally tested prototype detector prepared for the work demonstrated that a detector based on the BC-720 scintillation material did not exhibit necessary performance for neutron field measurements. In particular the distinctive neutron capture peak in the MCA spectrum, required for discrimination against gamma radiation in neutron spectrometry, was missing.

The pure light transport experiment carried out in investigating the light output and collection uniformity, also showed good agreement with simulations. Optical transport processes that take place in the scintillation materials BC-408 and BC-720 were successfully modeled using a Monte Carlo simulation program, for a solid rectangular geometry (BC-408), and for a hemisphere, half-hemisphere, and a quarter-hemisphere (BC-720).

Good agreement was achieved between the actual physical experimental measurements and the predictions of the light transport model. This agreement motivated a further study of geometry optimization, which investigated the issues of the light output and collection uniformity for a hemisphere and its alternative geometries: half- and a quarter-hemisphere. The results of this geometrical study showed no obvious advantage in subdividing a hemispherical lightguide into two or four smaller sections. For the tested model (internal layer – diffuse reflector, external layer – specular reflector) the hemispherical design shows better results both at absolute light collection and (lower)

variation of the light output. Simulations limited to the layer of Plexiglas demonstrated that light transport in a transparent material would not degrade the neutron signal provided that sufficient care is taken to achieve the highest possible reflection coefficient on all surfaces. Therefore, the original model made of BC-454 transparent scintillator, would be capable of discriminating between the neutron and gamma radiation, and is recommended for a prototype of the studied detector. Also, it was demonstrated that having both (internal and external) layers of the detector coated with “reflective” paint will maximize light yield and its collection uniformity.

APPENDIX 1. Sample Simulation Reports

Case #1:

a). Hemisphere: "Point source" located at 30 cm from the bottom

Photon generation in material: 2

X: 70.1554 to 70.1554

Y: 0 to 0

Z: 29.2270 to 29.2270

***** Simulation Report *****

Photons Counted:	0.46%
Photons Escaped:	0.20%
Photons Bulk Absorbed:	5.67%
Photons Surface Absorbed:	93.68%
Photons Timed Out:	0.00%

Total DSI events:	6037719
Refraction:	3418312
Internal Reflection	2209374 (36.5929 %)
Fresnel Reflection:	410033

b). Hemisphere: "Point source" located at 90 cm from the bottom

***** Simulation Report *****

Photons Counted:	2.24%
Photons Escaped:	0.57%
Photons Bulk Absorbed:	5.57%
Photons Surface Absorbed:	91.63%
Photons Timed Out:	0.00%

Total DSI events:	6318306
Refraction:	3645133
Internal Reflection	2262256 (35.8048 %)
Fresnel Reflection:	410917

Half-Hemisphere

a). Half-Hemisphere: "Point source" located at 30 cm from the bottom

***** Simulation Report *****

Photons Counted: 0.38%
Photons Escaped: 0.15%
Photons Bulk Absorbed: 5.00%
Photons Surface Absorbed: 94.47%
Photons Timed Out: 0.00%

Total DSI events: 2860330
Refraction: 1620212
Internal Reflection 1045576 (36.5544 %)
Fresnel Reflection: 194542

b). Half-Hemisphere: "Point source" located at 90 cm from the bottom

***** Simulation Report *****

Photons Counted: 1.96%
Photons Escaped: 0.41%
Photons Bulk Absorbed: 4.89%
Photons Surface Absorbed: 92.74%
Photons Timed Out: 0.00%

Total DSI events: 2968886
Refraction: 1710181
Internal Reflection 1064134 (35.8429 %)
Fresnel Reflection: 194571

c). Quarter-Hemisphere: "Point source" located at 90 cm from the bottom

***** Simulation Report *****

Photons Counted: 0.33%
Photons Escaped: 0.11%
Photons Bulk Absorbed: 4.54%
Photons Surface Absorbed: 95.02%
Photons Timed Out: 0.00%

Total DSI events: 1411351
Refraction: 799601
Internal Reflection 516053 (36.5645 %)
Fresnel Reflection: 95697

c). Quarter-Hemisphere: “Point source” located at 90 cm from the bottom

******* Simulation Report *******

Photons Counted:	1.80%
Photons Escaped:	0.29%
Photons Bulk Absorbed:	4.40%
Photons Surface Absorbed:	93.51%
Photons Timed Out:	0.00%
Total DSI events:	1437425
Refraction:	827315
Internal Reflection	515259 (35.8460 %)
Fresnel Reflection:	94851

Note: Total number of 1 million photons was simulated for each case.

APPENDIX 2. Sample Input File for DETECT
Hemispherical geometry with a 'Point Source' light generation mode.

; Defining Materials...

DMAT1,2.36N

DMAT2,1.49N,7600AD

DMAT3,1.5N

; Defining Finishes...

DFIN1,PAINT,0.90RC

DFIN2,DETECT

DFIN3,POLISH

DFIN4,METAL,0.965RC

; Defining Geometry...

DPLN1,0.0Z

DPLN2,76Z

DPLN3,96Z

DPLN4,98Z

DCYL1,10R

DSPH1,64R

DSPH2,SPH1,2R

DSPH3,SPH2,10R

COMP1,MAT1

SURF,FIN1,SPH1,RL

SURF,FIN3,SPH2,RS,C2

SURF,FIN4,PLN1,ZL

DPT1,66Z

DPT2,76Z

DPT3,76Z,10X

DCONE1,PT1,PT2,PT3

COMP2,MAT2

SURF,FIN3,SPH2,RL,C1

SURF,FIN4,SPH3,RS

SURF,FIN3,CONE1,RL,C3

SURF,FIN4,PLN1,ZL

COMP3,MAT2

SURF,FIN3,CONE1,RS,C2

SURF,PLN2,ZS

COMP4,MAT2

SURF,PLN2,ZL

SURF,FIN3,CYL1,RS
SURF,FIN3,PLN3,ZS

COMP5,MAT3
SURF,FIN3,PLN3,ZL
SURF,FIN3,CYL1,RS
SURF,FIN2,PLN4,ZS

LIFE30000
SEED 3
GEN,MAT2,70.1554XS,70.1554XL,0.0000YS,0.0000YL,29.2270ZS,29.2270ZL

RUN10000

END

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IMAGE EVALUATION TEST TARGET (QA-3)

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