1 Calibration of Cherenkov Detectors for Monoenergetic 2 Photon Imaging in Active Interrogation Applications

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5 Abstract

6 Active interrogation of cargo containers using monoenergetic photons offers
7 a rapid and low-dose approach to search for shielded special nuclear materials.
8 Cherenkov detectors can be used for imaging of the cargo provided that gamma
9 ray energies used in interrogation are well resolved, as the case in $^{11}\text{B}(\text{d},\text{n}-$
10 $\gamma)^{12}\text{C}$ reaction resulting in 4.4 MeV and 15.1 MeV photons. While an array
11 of Cherenkov threshold detectors reduces low energy background from scatter
12 while providing the ability of high contrast transmission imaging, thus confirm-
13 ing the presence of high-Z materials, these detectors require a special approach
14 to energy calibration due to the lack of resolution. In this paper, we discuss
15 the utility of Cherenkov detectors for active interrogation with monoenergetic
16 photons as well as the results of computational and experimental studies of their
17 energy calibration. The results of the studies with sources emitting monoen-
18 ergetic photons as well as complex gamma ray spectrum sources, for example
19 ^{232}Th , show that calibration is possible as long as the energies of photons of
20 interest are distinct.

21 *Keywords:* Cherenkov detectors, active interrogation, imaging, shielded
22 special nuclear material

23 1. Introduction

24 Cargo screening using radiation monitors is an integral part of US safety
25 and security strategy [1], especially when searching for illicit transportation of
26 small volumes, on the order of 100 cm³, of special nuclear material (SNM).The

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27 impracticality of physically opening and inspecting each air, ground, or sea
 28 container resulted in the development of a number of radiation-based scanning
 29 techniques, both passive [2] using the signatures of the material and active [3–5]
 30 with an external radiation source. Passive techniques have an advantage of low
 31 cost and relative simplicity as compared to active interrogation systems, but
 32 rely on naturally emitted radiation from SNM, which is relatively easy to con-
 33 ceal with proper shielding [6]. One of the major problems associated with active
 34 interrogation methods is dose delivered to the cargo and operators. An active
 35 interrogation system capable of producing monoenergetic photons, that are a
 36 product of low-energy nuclear reactions, for example $^{11}\text{B}(\text{d},\text{n}-\gamma)^{12}\text{C}$ [7–10], can
 37 be utilized to penetrate the shielding and reveal the SNM inside while delivering
 38 dose that is significantly lower than the dose associated with bremsstrahlung-
 39 based systems. Coupling these high energy monoenergetic photons with an
 40 array of detectors enables the gamma ray transmission through the cargo for
 41 the production of a high contrast planar image as well as to study properties of
 42 the cargo specific to nuclear materials, for example delayed neutron and gamma
 43 emissions. A conceptual illustration of transmission imaging using an array of
 44 detectors is shown in Figure 1. In this paper, we discuss the results of computa-
 45 tional and experimental studies of energy calibration performed with Cherenkov
 46 detectors designed specifically for coupling with an active interrogation system
 47 for gamma ray transmission imaging [11] The image produced is a measure of
 48 the atomic number, Z , of the material for a rapid identification of heavy items
 49 in a cargo container.

50 2. Description of the system

51 2.1. Source of monoenergetic photons

52 Multiple low-energy nuclear reactions can produce high energy gamma rays [7],
 53 but for the purposes of this paper we will focus on an extension of one system
 54 in particular [10, 12]. In this system, a compact accelerator is used to direct
 55 deuterons into a ^{11}B target, resulting in $^{11}\text{B}(\text{d},\text{n}-\gamma)^{12}\text{C}$ reaction. This leaves

Figure 1: Conceptual design and principle of operation of imaging system based on monoenergetic photons

¹²C in excited states which produce 4.4 MeV and 15.1 MeV gamma rays at high intensity as well as less intense gamma rays during carbon's return to the ground state. By time gating the data acquisition with the accelerator pulse, it is possible to filter out undesired products from nuclear reactions caused by the emission of high energy neutrons and focuses on the fastest de-excitations of the carbon nucleus. Experimental results validating this method can be found in Sheffield and Taducci [13].

The 4.4 MeV and 15.1 MeV gamma rays are used to produce a transmission image of the cargo, identifying relative Z of the material. The 4.4 MeV photon interactions are heavily dominated by Compton scattering, therefore are a measure of the electron density of the material which is a function of the Z. The 15.1 MeV interactions are dominated by pair-production for mid- and high-Z materials. Cherenkov detectors are a part of the imaging approach of the system which provide high-frequency and low-background performance.

2.2. Cherenkov detectors

High radiation flux systems pose unique detection challenges which Cherenkov detectors are well suited for. High energy resolution is not a priority for this system since the 4.4 MeV and 15.1 MeV gamma rays are well separated. Such a system must be scalable, customizable, composed of inexpensive materials, resistant to background radiation, and capable of processing high interaction

76 rates. Cherenkov light emission [14, 15] is a response of matter to the mo-
 77 tion of a charged particles traveling at a speed exceeding the phase velocity of
 78 light in that medium. It is commonly produced in dielectric materials through
 79 Compton electrons or pair-production electrons and positrons. The intensity
 80 of light produced by this process is much less than that of luminescence (the
 81 basis for scintillation detector operation) requiring sensitive optical photon de-
 82 tection equipment such as a photo-multiplier tube (PMTs) or solid state silicon
 83 photomultiplier (SiPMs). On a positive side, typical scintillator detectors have
 84 a decay time measured in microseconds while Cherenkov radiation is nearly
 85 instantaneous and with fast pulse processing equipment can be measured in
 86 picoseconds. Other unique properties distinguishing Cherenkov radiation from
 87 luminescence are directionality, UV-concentrated photon spectrum, and energy
 88 threshold that is related to the dielectric constant of the chosen material.

89 Cherenkov radiation is emitted in a forward cone in the direction of the
 90 charged particle which is also forward peaked at high incident gamma ray en-
 91 ergies (above 1 MeV). This cone is emitted in the direction of the PMT or
 92 other photon sensing device making the geometrical considerations of the de-
 93 tector crucial for peak performance. The inherent energy threshold properties of
 94 Cherenkov are based on the refractive index of a material which sets the phase
 95 velocity of the speed of light in that material. The refractive indices of materi-
 96 als can be finely tuned to produce an energy threshold rejecting particles below
 97 a certain energy suppressing background radiation. Significant background re-
 98 duction focuses on the energies desired thus further reducing the demands on
 99 the detector allowing for faster scanning times. Figure 2 illustrates the relation-
 100 ship of the Cherenkov threshold to the energy of the incident gamma rays and
 101 subsequent Compton electrons.

102 Since there are neutrons present in the $^{11}\text{B}(\text{d},\text{n}-\gamma)^{12}\text{C}$ reaction, the Cherenkov
 103 radiator was chosen to be resistant to neutron activation and other neutron re-
 104 actions such as the $\text{H}(\text{n},\gamma)\text{D}$ capture reaction. These secondary reactions can
 105 introduce photons generated inside the detector adding massive overhead to the
 106 system and degrading the dual monoenergetic benefits of the initial nuclear re-

107 action. After considering and testing many materials, Quartz, GE type 214 was
 108 selected as a final radiator option due to a very pure SiO_2 crystalline lattice
 109 structure with excellent light transmission properties, especially in the UV part
 110 of the spectrum.

111 Quartz provides a unique set of material properties well suited to this ap-
 112 plication. It has a higher density than most other materials typically used for
 113 Cherenkov radiation, for example water or acrylic, allowing to use smaller de-
 114 tectors to match the photon interaction probability. Quartz is not hydrophilic
 115 like many scintillator crystals and is very resistant to thermal expansion in the
 116 anticipated operating temperature range, 0 to 40°C. The internal light trans-
 117 mission is efficient due to high purity of material and high internal reflectivity,
 118 allowing more optical photons to reach the PMT. The geometry chosen for this
 119 source is rods 2.5 cm in diameter by 15.2 cm in length. To maximize optical
 120 photon transmission efficiency, the quartz is wrapped with PTFE tape reflector,
 121 then light proofed with a rubber heatshrink. This combination has proved to
 122 be a very efficient, rugged Cherenkov radiator design that is very resistant to
 123 neutron activation and can be used in the field under any weather conditions.

124 The absolute energy threshold for a detector made from this type of quartz,
 125 SiO_2 , is calculated to be 0.336 MeV. This threshold is calculated assuming max-
 126 imum energy transfer in a Compton scattering event which is rarely the case,
 127 especially at lower energies. Signal generation will be very low until approxi-
 128 mately 0.55 MeV, referred to here as effective threshold, where the partial energy

Figure 2: Natural threshold of Cherenkov radiation as a function of refractive index.

transfer consistently imparts enough kinetic energy to the Compton electron to generate Cherenkov radiation. A large portion of background radiation is below this threshold and therefore will not produce any signal in the detector.

3. Overview of the approach to energy calibration with Cherenkov detectors

Energy calibration for scintillation detectors is a well-understood process that uses either the maximum or centroid of a peak in the energy histogram to derive the incident particle energy versus energy bin relationship. This method does not work for Cherenkov radiation since there are no well resolved peaks due to low levels of light emission for particles in MeV energy range. Instead, we must consider features in the energy histogram and relate them to the physics taking place. Using features such as the tail slopes, inflection points, and shoulder we can assign maximum energy deposition, most probable Compton electron energy corresponding to the energy of incident photon, and average energy deposited respectively.

In the detector calibration approach offered here, the primary source of particle information is the “tail” of the energy histogram as shown in Figure 3. In an ideal scenario, the location of the tail with respect to the energy bin axis will indicate the energy calibration point. However, very high flux situations

Figure 3: Cherenkov emission spectra associated with different sources. All data have been normalized to 1 to account for the differences in activity of these sources.

148 produced by accelerators are far from ideal. The Cherenkov detectors were de-
 149 signed to work in such environments; although statistically rare due to the fast
 150 nature of the electromagnetic emission taking place, pulse pile-up and multiple
 151 particle interaction coincidences occur affecting the spectrum tail. Thus, the
 152 location where the tail meets the energy bin axis cannot be considered as the
 153 maximum energy transferred. When analyzing the tail of a Cherenkov spectrum
 154 generated in a high flux environment, we look at the inflection point of the tail
 155 where it appears as two linear relationships meet as shown in Figure 3. Observ-
 156 ing the pile-up effects in various experimental conditions and extrapolating the
 157 linear part of the spectrum tail, we choose to cut off everything below 0.2% of
 158 the total signal. This metric is specific to the detector and electronics and will
 159 vary for different systems. However, using this cutoff metric, we can assign the
 160 location where the energy histogram intersects the new x-axis as the maximum
 161 energy deposited from the incident photon which provides the relationship for
 162 channel vs. incident particle energy needed for energy calibration. This relation,
 163 once determined for the detector, will hold for most sources, unless very high
 164 fluxes are experienced as compared to the reference system. To be consistent
 165 in assigning this point, we use an algorithm we designed to analyze the slope of
 166 the remaining tail and solve for the ADC channel where the linear relationship
 167 meets the cutoff. This algorithm takes into account the slope of the tail as well
 168 as the spread in the data to indicate event pile-up and coincidence.

169 **4. Modeling and simulation with Geant4**

170 The performance of the detectors has been characterized and optimized us-
 171 ing Monte Carlo simulations. Geant4.10 was used to model the detector due to
 172 the capability of advanced optical photon transport, control of material prop-
 173 erties, and detailed physics including Cherenkov radiation in particular. The
 174 Geant4 toolkit [16?] provides a flexible framework for the simulation of par-
 175 ticle transport and interaction with matter. The quality of the simulations
 176 relies heavily on user inputs for properties and physical processes of interest.

177 When applied to Cherenkov detectors, Geant4 has the capability of triggering
178 and tracking optical processes, which include the generation of Cherenkov pho-
179 ton by a charged particle. Rayleigh scattering, bulk absorption and reflection-
180 refraction media-boundary interactions are also part of the optical processes and
181 are wavelength-dependent. Mechanical and optical properties of quartz from
182 experimental measurements were combined with information provided by the
183 manufactures including the efficiency and sensitivity of photomultiplier tubes.
184 Modeling studies included the quartz crystal size and shape combined with a
185 variety of PMTs to determine the optimal configuration for the given applica-
186 tion.

187 Prior to detector construction for active interrogation applications, its ef-
188 ficiency has been studied as a function of gamma ray energy and the PMT
189 properties assuming 100% geometric efficiency. The sources included ^{137}Cs ,
190 ^{60}Co , ^{232}Th , PuBe, and AmBe, as available in the laboratory for experimental
191 validation. AmBe and PuBe sources were used as a surrogate for the lower end
192 of the deuteron-induced spectrum corresponding to the monoenergetic photons
193 of 4.4 MeV. Both of these sources emit 4.4 MeV gamma rays from the same tran-
194 sition as the accelerator driven source, one of the excited states of carbon. Since
195 the actual $^{11}\text{B}(\text{d},\text{n}-\gamma)^{12}\text{C}$ reaction also produces copious neutrons, hydrogenous
196 materials were studied in order to understand the shielding needs of experimen-
197 tal accelerator-driven reactions. AmBe and PuBe sources were combined with
198 acrylic or poly cylinders producing neutron capture by hydrogen resulting in a
199 2.2 MeV gamma ray. Materials rich in hydrogen that will be used to shield neu-
200 trons during the active interrogation will create a significant contribution to the
201 signal due to the capture reaction. By including the neutron in the simulation,
202 an accurate estimate of the lower end of the anticipated spectrum is obtained
203 while also allowing for preliminary validation and transmission experiments to
204 be carried out. The summary of the simulated efficiency for the four sources
205 is shown in Table 1. This metric is the theoretical maximum as it counts even
206 single photoelectrons generated in the PMT. In experiment, some of the signal
207 will be filtered out as dark current in the PMT.

Table 1: Detector efficiency by source

Source	Photon energy (keV)	2" long radiator	4" long radiator
^{137}Cs	662	19.6%	25.4%
^{60}Co	1173 and 1332	33.9%	51.5%
^{232}Th	2614 (maximum)	30.8%	49.1%
PuBe	4440	25.8%	45.8%

208 The detector efficiency is dependent on the energy of the photon as well
 209 as the length of the detector. Most scintillating detectors have a higher effi-
 210 ciency with ^{137}Cs (662 keV gamma ray) than they do at higher energy sources
 211 which is not the case for Cherenkov detectors. The effective energy threshold
 212 for photon-generated signal of these detectors is about 550 keV, meaning the
 213 electron must receive a large majority of the energy during the Compton scatter.
 214 The scattering angle probability is closer to isotropic than forward peaked at
 215 this energy as predicted by the Klein-Nishina formula. This means that most
 216 Compton interactions will not transfer enough energy to the electron to gen-
 217 erate Cherenkov radiation. The relationship between photoelectrons produced
 218 in the PMT and the incident particle energy can be deduced similarly to the
 219 Cherenkov detector method introduced earlier. However, since the simulation
 220 is sequential, there is no pile-up or multi-particle coincidence to be observed.
 221 The highest number of photoelectrons produced corresponds to the maximum
 222 energy transfer to the Cherenkov radiating material. To ensure we are consid-
 223 ering statistically relevant results as well as keeping the simulation consistent
 224 with experimental studies, we choose the 0.2% cutoff for the energy calibration.
 225 Considering the physics behind the interactions, the total energy deposited is
 226 less than the energy of the photon emitted by the source. However, since this
 227 is common across all interactions in the energy range considered, the relation
 228 between the photon energy can be established as shown in Figure 4.

229 The points on the plot represent the maximum gamma ray energies of the

Figure 4: Simulated energy calibration of the 2-inch long detector

sources used from low to high: ^{137}Cs , ^{60}Co , ^{232}Th , and PuBe , respectively. The results are shown for the 2-inch long detector, and the 4-inch long design displays a nearly identical relationship. The simulation predicts a highly linear relation between the energy deposited in the detector and the number of photoelectrons created in the PMT across this incident photon energy range. These relationships are used to produce the energy calibrated histograms for the 2-inch long detector fabricated for experimental testing as shown in Figure 5. It should be noted that additional studies are underway to include 15.1 MeV gamma rays for the future analysis. Due to higher energy of the gamma ray, the interactions are a combination of Compton scattering and pair production which may lead to deviation from linearity observed in Figure 4. The x-axis is the number of photoelectrons produced calibrated to incident photon energy in the R292 PMT, which has high UV sensitivity. This curve is not exactly what is expected experimentally because the photoelectrons have some energy distribution to them where the simulation assumes a constant energy.

5. Experimental results

Multiple detector designs have been built and tested including polymethyl methacrylate (PMMA) and quartz to understand detector properties as a function of gamma ray energy and detector length as well as for computational model validation. An array of detector samples is shown in Figure 6. The final validation was done with two quartz detectors of slightly different designs: a 2-inch

Figure 5: Calibrated spectral response of the 2-inch long detector (simulation)

251 long crystal coupled with a Hamamatsu R292 PMT and a 4-inch long crystal
 252 coupled with a R6095 PMT. Experimental energy calibration is more convoluted
 253 than computational. Statistically, event pile-up and multiplicity may become
 254 an issue even though Cherenkov radiation is a nearly instantaneous response to
 255 the Compton electron; however, the effects are minimized when compared to
 256 scintillators. As described in the calibration method, the first step is to apply a
 257 cut to the normalized counts, 0.2% of the total signal in this case, to subtract
 258 the contribution of noise. This also cuts off the signal from addition of two
 259 gamma rays as well as muon interactions which are much less probable than the
 260 photon interaction.

261 Even though the size of the detector is small, an occasional muon interaction
 262 deposits a large amount of energy in the detectors and can cause excess signal
 263 in any energy bin. Next, the slopes of the tails are analyzed, and the location
 264 where they meet the x-axis (ADC channels) is correlated to the channel of full
 265 energy deposition (photopeak). These intersections are related to the maximum
 266 gamma energy emitted from the source. Figure 7 shows the resulting energy
 267 calibration curve for the 2-inch long detector. Even though the results are
 268 pedestal-subtracted, the nonlinearity of Cherenkov light generation near the
 269 threshold region precludes low-energy photons from being used in calibration.
 270 Photon energy of 661.7 keV corresponding to ^{137}Cs is the lowest energy used.

271 Similarly to the computational results, the experiments show a strong linear

272 relationship between energy deposited in the detector and the ADC channel.
273 This trend line equation is used to convert the experimental data from ADC
274 channels to energy of incident photons. The 2-inch long detector produced a
275 very similar relationship and an equation for the unique energy calibration. The
276 resulting energy calibration can be seen in Figure 8 for the 2-inch long detector.

277 When considering the Cherenkov spectra, it is evident that there are no well-
278 resolved peaks produced by the detector. Instead, spectral information can be
279 gathered from slopes of the tails and location of changes in slope, shoulders, and
280 the data. In the lower energy range, there is little usable data. The peaks and
281 shoulders that are most evident are related to the average energy transferred
282 to the Compton electron in a scattering event. The average energy transferred
283 to a Compton electron in a 4.4 MeV scattering event from the PuBe/AmBe
284 source is about 2.7 MeV. This is where the “peak” can be seen in Figure 8 in
285 the PuBe spectrum. It is important to note the effective Cherenkov radiation
286 energy threshold for a photon in this material is about 550 keV, and the linearity
287 of the energy calibration breaks down as this limit is approached. Performing
288 an energy calibration based on the three higher energy sources (^{60}Co , ^{232}Th ,
289 and PuBe) yields a more accurate calibration among those energies, but the 662
290 keV from the ^{137}Cs virtually disappears from the plot. For later experiments
291 including 15.1 MeV photons, the 662 keV will be omitted from the energy
292 calibration.

Figure 6: Experimental setup of various Cherenkov detectors.

Figure 7: Experimental energy calibration of the 4-inch long detector

Figure 8: Calibrated spectral response of the 2-inch long detector (experimental)

293 The 4-inch long detector uses the R6095 which operates on a very different
 294 design than the traditional box-and-grid style R292 used in the 2-inch long
 295 detector. The R292 is more efficient when considering total photoelectrons
 296 created vs. photoelectron collected, but the electron transit time is much longer,
 297 and the pulses are stretched over a longer time period. This effect is on the order
 298 of 100 ns per pulse, where the pulse from the R6095 can be accepted in about
 299 50 ns. Figure 9 shows the same experiments performed with the 4-inch long
 300 detector with the energy calibration performed by the same method.

301 Due to more favorable time properties of the R6095 PMT, the energy cali-
 302 bration for the 4-inch long detector appears to be more accurate than the 2-inch
 303 long detector. Another characteristic to notice is the formation of peaks in the
 304 region less than 1 MeV. These peaks are misleading because they are formed
 305 due to the less efficient photoelectron collection of R6095 PMT type. When

Figure 9: Energy calibrated experimental data from the 4-inch long detector.

306 few photoelectrons are produced, a large percentage could be lost at each stage.
 307 The more photoelectrons generated in the first stages, the more consistent the
 308 signal is. Even though the 4-inch long detector is much longer, it registers fewer
 309 counts for the 662 keV photons than the 2-inch long detector did at the same
 310 distance from the source. The ratio of the maximum efficiency to the ^{137}Cs
 311 efficiency for each detector is much lower for the 4-inch long due to the PMT
 312 type. However, it is possible to see the difference between the combined peak
 313 from ^{60}Co (1.17 and 1.33 MeV gamma rays) and ^{232}Th (0.911 and 0.969 MeV
 314 gamma rays).

315 The PuBe and AmBe sources were used with and without hydrogenous ma-
 316 terial present around the sources. This produces a significant number of 2.2
 317 MeV gamma rays from the (n,γ) reaction on hydrogen. Figure 10 shows the
 318 experimental results of detection of gamma rays from an AmBe source with and
 319 without large poly cylinders beside the source. At the maximum gamma ray en-
 320 ergy of 4.4 MeV, the two spectra line up very well. The relative contribution of
 321 the 2.2 MeV gamma rays is very apparent in the run with polyethylene present.
 322 This mimics the low end of the accelerator driven source very closely. The av-
 323 erage energy transferred to a Compton electron in a 2.2 MeV scattering event
 324 is about 1.3 MeV which is where the shoulder can be seen in the data where
 325 the poly is present. Figure 11 illustrates the potential technique of Cherenkov
 326 detector energy calibration. The terminal energy (ADC bin or computational

327 number of photoelectrons) of the peak is estimated. The estimate can be plot-
 328 ted against the corresponding energy of the particle. The slope of the line can
 329 be used to calculate the calibration parameters. Besides the convenience of this
 330 method, using the terminal energy guarantees that when the detection threshold
 331 is placed, it will not be exceeded by a particle of lesser energy. As is evident from
 332 the comparison, computational and experimental results are in good agreement.

Figure 10: Comparison of moderated and unmoderated experimental results from AmBe source

Figure 11: Correlation of simulation and experimental energy calibration for 2-inch long detector

333 6. Conclusions

334 Two quartz detector designs were designed, optimized using Geant4 mod-
 335 eling and simulations, fabricated, and tested with various sources to validate

the simulation predictions. The computational and experimental results were calibrated using a linear relationship of photon energy and photoelectrons or bins, respectively. The range of incident energies shows good linearity once the energy is sufficiently above the threshold. However, it is expected that above some energy, dependent upon the material, the linearity will break down. Once the 15.1 MeV photons are introduced to the testing, the energy calibration will be tested for other relations, for example quadratic, as well as exclude the ^{137}Cs for improved accuracy.

These detectors will further be tested with an ion accelerator where the high energy monoenergetic photons can be produced via the nuclear reactions. Upon characterization of the signal generated from the high energy photons, the energy calibration method discussed here will be applied. After that, transmission studies through various areal densities atomic numbers will be completed in preparation to apply a large scale array of these detectors for cargo imaging purposes. This energy calibration technique opens the door to spectrum deconvolution, unfolding, of Cherenkov detectors. The process has been well proven with scintillators but not with Cherenkov detectors. Using information such as the slopes of the tails and shoulders as related to energies it is in theory possible to perform such calculations. More studies are on the way to understand the behavior of Cherenkov detectors in the environment with significant scattering as well as when several photon energies that are close together, for example 12.7 MeV and 15.1 MeV gamma rays associated with another proposed reaction $^{12}\text{C}(\text{p},\text{p}'\gamma)$, are present.

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