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TITLE: MONTE CARLO SIMULATION OF GAS CERENKOV DETECTORS

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Monte Carlo Simulation of Gas Cerenkov Detectors

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ABSTRACT

Theoretical study of selected gamma-ray and electron diagnostics necessitates coupling Cerenkov radiation to electron/photon cascades. A Cerenkov production model and its incorporation into a general geometry Monte Carlo coupled electron/photon transport code is discussed. A special optical photon ray-trace is implemented using bulk optical properties assigned to each Monte Carlo zone. Good agreement exists between experimental and calculated Cerenkov data in the case of a carbon-dioxide gas Cerenkov detector experiment. Cerenkov production and threshold data are presented for a typical carbon-dioxide gas detector that converts a 16.7 MeV photon source to Cerenkov light, which is collected by optics and detected by a photomultiplier.

INTRODUCTION

Computational methods of coupled electron/photon transport are now widely used to solve a variety of radiation transport problems[1]. Of these methods Monte Carlo provides the most comprehensive treatment of cascade generation and transport in generalized geometry. Cascade production, transport, and penetration through matter are the essential tasks. The cascade produced by coupling electrons and photons is often complex and may include photoelectrons, Compton, pair, Auger, and knock-on electrons; and bremsstrahlung, characteristic X-rays, and annihilation photons. Integrating Cerenkov photon production into the cascade provides a new capability useful in the investigation of certain detector concepts considered in photon and electron diagnostics.

THEORETICAL ASPECTS

The physics of Cerenkov production was initially formulated by Frank and Tamm[2]. The Cerenkov effect is the coherent response of a medium to the passage of a charged particle whose velocity is greater than the wavelength-dependent photon phase velocity in that medium. The resulting Cerenkov electromagnetic wavefronts along the particle track constructively interfere (via Huygens' Principle) at a unique angle θ

relative to the direction of the charged particle. Angle θ is defined by the Cerenkov relation[3]

$$\cos \theta = \frac{1}{\beta n(\lambda)} \quad (1)$$

where β is the ratio of particle velocity to the velocity of light in vacuum and $n(\lambda)$ is the wavelength-dependent index of refraction for that medium. For a specific medium the threshold energy of Cerenkov production corresponds to a particle velocity β_0 . For electrons, the number of Cerenkov photons N produced per unit pathlength l as a function of wavelength is

$$\frac{dN}{dl} = 2\pi\alpha \int_{\lambda_1}^{\lambda_2} \left[1 - \frac{1}{\beta^2 n^2(\lambda)} \right] \frac{d\lambda}{\lambda^2}, \quad (\lambda_2 > \lambda_1), \quad (2)$$

where α is the fine-structure constant. Production increases toward shorter wavelengths and is not allowed at wavelengths where $n(\lambda) < 1/\beta$, thereby defining the wavelength integration limits.

COMPUTER CODE MODEL

The ACCEPT[4] computer code, chosen as the basic modeling framework, is an extension of the work of Berger[5]. It uses condensed-history Monte Carlo for electron transport and conventional single-scattering Monte Carlo for photon transport. The random walk is executed within a three-dimensional combinatorial geometry approach similar to that found in the MORSE[6] code.

In condensed-history Monte Carlo electrons are transported in multiple-interaction pathlengths to which Cerenkov production must be directly linked. Cerenkov production within an assumed wavelength bandwidth and along a condensed-history pathlength is computed using Equation 2. Emission of a Cerenkov photon occurs at a point randomly selected along that pathlength. The emission angle, azimuthally symmetric about the electron direction, is chosen using the Cerenkov relation, Equation 1. Photon energy is approximated to be the mean energy of the wavelength bandwidth.

Cerenkov photons are generated from the infrared into the vacuum ultraviolet at very low energies (compared to the source energy); we do not transport these very low energy photons in the strict sense of the word. Instead, for each Cerenkov photon, a detailed ray trace is performed in the general three-dimensional Monte Carlo geometry with the appropriate optical elements included as an integral part of the geometrical description. The trajectory of an emitted Cerenkov photon moving through various three-dimensional zones is determined by a set of bulk optical properties assigned to each Monte Carlo zone. These wavelength-independent zonal bulk properties include the refractive index, absorption coefficient, specular and diffuse reflection fractions, and fractional light transmittance. The transmittance fraction and Snell's Law specify the number and direction of Cerenkov photons allowed into the next zone intercepted by the current ray. In summary, not only do these Monte Carlo simulations account for the production of the Cerenkov component, but also allow one to investigate a variety of optical systems for light collection. Previous Monte Carlo model simulations of Cerenkov radiation from monoenergetic electron beams incident on a gas Cerenkov detector (GCD) were performed by Mack and Jordan[7]. We now present results of calculations simulating a 16.7 MeV photon beam incident on a GCD filled with carbon-dioxide. GCD design considerations are also included in the discussion of these results.

GCD GEOMETRY

A schematic of the proposed GCD geometry is illustrated in Figure 1 and consists of a steel can structure, housing a converter foil, carbon-dioxide gas fill, collecting optics, and photomultiplier. The function of this GCD is to convert 16.7 MeV photons into a secondary electron source through interaction with a judiciously chosen converter foil. The secondary electrons enter the gas region and generate the usual cascade along with Cerenkov

Figure 1. Gas Cerenkov detector geometry including optics.

photons, if the electron energy is above threshold energy at the fill-gas pressure. In simulating the above system with the Monte Carlo model, Cerenkov photons are traced through the three-dimensional geometry with each Monte Carlo cell having its own set of optical boundary conditions. These boundary conditions include diffuse wall reflection, specular reflection off mirrors, and refraction through lenses. The optics system collects much of the Cerenkov light and directs it to the photomultiplier.

Design optimization entails the proper selection of converter-foil material and its thickness, given that the housing and optics are already chosen. Foil optimization involves fundamental considerations related to the energy-angle dependence of the secondary electrons produced by the photon beam as it interacts with the foil. Ideally the electrons would all have energies above threshold (> 12 MeV) and be highly forward-peaked. High-Z materials usually produce more secondary electrons but absorption processes prevent many from escaping the foil into the gas region to eventually produce Cerenkov photons. Furthermore, those electrons that manage to escape the foil and interact with the gas will have significant multiple-scattering angles associated with their trajectories. Such enhanced high-Z multiple-scattering produces too much angular spread of the escaping electrons and the Cerenkov they generate. Increasing angular spread reduces the collection probability to the photomultiplier.

Calculation of energy-angle spectra for lead, beryllium, and aluminum was accomplished using Monte Carlo, for foils of identical areal densities. Based primarily on these calculations aluminum was chosen as the converter foil material. The foil thickness must be optimized for maximum Cerenkov output in the gas and subsequent delivery to the photomultiplier. Cerenkov yield in the gas and the number that reach the photomultiplier are shown in Figure 2 for foil thicknesses (mils) of 10, 20, 40, 80, 120, 160, 320, 480, 640, 800, 1600, and 2400. Hereafter, all Monte Carlo calculations presented have one- σ relative errors of better than $\pm 10\%$.

Figure 2. Cerenkov yield vs aluminum foil thickness for the gas region (solid curve) and the number delivered to the photomultiplier detector (dotted curve). Carbon-dioxide pressure: 29.3 psia, photon beam energy: 16.7 MeV.

Consider the production in the gas (solid curve) as foil thickness is increased. Between 0 to 200 mils Cerenkov yield increases dramatically because electrons generated in the foil readily escape into the gas region before being degraded in energy to produce Cerenkov. As the foil thickness approaches an electron mean range, multiple-scattering and energy-loss effects begin to dominate, resulting in production saturation. As thickness increases well beyond an electron range, Cerenkov number slowly diminishes until the photon mean-free-path is approached. At this point Cerenkov production will rapidly decrease, primarily due to the onset of significant photon attenuation. Collection efficiency to the photomultiplier is indicated by the dotted curve in Figure 2. It quantifies the number of Cerenkov photons that reach the photomultiplier per source 16.7 MeV photon incident upon the detector geometry. Thus, there are two important efficiencies shown by Figure 2: 1) the foil efficiency in converting the photon beam into a secondary electron source that maximizes Cerenkov yield, and 2) the optical collection efficiency of Cerenkov photons to the photomultiplier. One other competing factor in the choice of foil thickness is the formation of secondary electrons below threshold that can result in an undesirable background at the detector location. This effect is reduced by using thinner foils of lower-Z materials and was another important factor in selecting aluminum as the foil material.

Cerenkov threshold curves, as shown in Figure 3, depict Cerenkov production in the gas region (at constant pressure) as the photon beam energy changes and the converter-foil material and thickness remain fixed. As the threshold energy is approached from higher beam energies, Cerenkov production decreases rapidly toward zero (by definition). When the beam energy is increased well beyond threshold, production increases

Figure 3. Cerenkov threshold curve for a 20 mil aluminum converter foil. Solid curve, gas region; dotted curve, photomultiplier detector region.

in an asymptotic manner. This behavior can be deduced from Equation 2 in the limit as $\beta \rightarrow 1$. The dotted curve of Figure 3 is another form of the threshold curve but from the photomultiplier detector viewpoint. It depends on the energy-angle characteristics of foil-produced secondary electrons and their ability to create Cerenkov photons that can reach the photomultiplier. When used in conjunction with the solid curve for the gas region, it is an indication of collection efficiency at the photomultiplier for a specific photon beam energy.

CONCLUDING REMARKS

A powerful and quite general computational tool has been developed that enables the computational physicist to investigate new areas of electron and photon diagnostics through analysis of Cerenkov radiation. Partial experimental verification of the model has been completed and more will follow. Coupling Cerenkov production to the electron/photon cascade in generalized geometry, and allowing the Cerenkov photons to interact with bulk optical properties, results in a capability with which theoretical design of various Cerenkov detection systems can now proceed routinely. Other related topics for future consideration include implementing a wavelength-dependent refraction index, and transition radiation sources.

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