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Monte Carlo Simulation of a Plastic Scintillator Detector with Photomultiplier Tube: Statistical Noise Analysis and Light Trapping Efficiency

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Radiation detectors based on plastic scintillators coupled to photomultiplier tubes (PMTs) are widely used in nuclear physics, radiation security, and nuclear medicine. However, the final electrical signal exhibits inherent statistical fluctuations that limit the detector's energy resolution. This work presents a comprehensive Monte Carlo simulation implemented in Python that models the entire detection chain, from scintillation photon generation to the formation of the electrical pulse at the PMT anode.

The simulation incorporates: (i) photon generation following a Poisson distribution with a mean of 10,000 photons per MeV of deposited energy, (ii) isotropic emission from random positions within a $20\times10\times5$ mm^3 rectangular volume, (iii) light trapping via total internal reflection considering a refractive index of 1.58 (plastic) and a critical angle of 39.3°, (iv) photon-to-electron conversion at the photocathode with 25% quantum efficiency modeled as a binomial process, (v) electron multiplication across 10 dynode stages with a total gain of 4^10 ≈ 10^6, and (vi) temporal pulse shaping using a double-exponential function with characteristic rise time (τ_r = 2 ns) and decay time (τ_d = 30 ns).

Results show that only 11-15% of generated photons are effectively trapped and contribute to the signal, amplifying the Poisson noise beyond naive expectations. The simulated energy resolution follows the theoretical trend $\propto 1/\sqrt{E}$, achieving 8.5% at 1 MeV, consistent with experimental data reported in the literature for commercial plastic scintillators.

Scintillation detector, photomultiplier tube, Monte Carlo simulation, Poisson statistics, total internal reflection, energy resolution.

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