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Photodetectors for scintillator proportionality measurement

William W. Moses [a,*], Woon-Seng Choong [a], Giulia Hull [b], Steve Payne [b], Nerine Cherepy [b], John D. Valentine [b]

[a] Lawrence Berkeley National Laboratory, USA
[b] Lawrence Livermore National Laboratory, USA

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ABSTRACT

We evaluate photodetectors for use in a Compton Coincidence apparatus designed for measuring scintillator proportionality. There are many requirements placed on the photodetector in these systems, including active area, linearity, and the ability to accurately measure low light levels (which implies high quantum efficiency and high signal-to-noise ratio). Through a combination of measurement and Monte Carlo simulation, we evaluate a number of potential photodetectors, especially photomultiplier tubes and hybrid photodetectors. Of these, we find that the most promising devices available are photomultiplier tubes with high (~50%) quantum efficiency, although hybrid photodetectors with high quantum efficiency would be preferable.

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1. Introduction

The Compton Coincidence Technique [1–3] is commonly used to understand scintillator proportionality. Measurements of scintillator proportionality are important, as deviations from proportionality degrade the energy resolution for a scintillator material [4–10]. The Compton Coincidence Technique measures the electron response—the dependence of the scintillator luminosity (photons/MeV) on the energy of the quanta (in this case, electrons) that excite it. While the Compton Coincidence apparatus we have developed is described in detail in [11,12], the basic technique is to have a monoenergetic gamma ray from an isotopic source (usually 662 keV emissions from Cs-137) undergo Compton scatter within a scintillator sample. The energy of the scattered gamma ray is measured by a high-purity germanium (HPGe) detector, and the amount of energy deposited in the scintillator is given by the difference between the initial and scattered gamma ray energies. The scintillator is coupled to a photodetector that measures the amount of light produced by this interaction, and so allows the scintillator luminosity to be calculated at a variety of energies. A sample electron response measurement is shown in Fig. 1a. The underlying measurement for each of the data points in Fig. 1a, which is the pulse height distribution recorded by the photomultiplier tube (PMT) when the scintillator is excited with monoenergetic Compton electrons, is shown in Fig. 1b for three different electron energies.

The requirements placed on the photodetector in these systems are quite stringent. In general, one needs to accurately measure the light produced by a scintillator crystal (our "standard" scintillator geometry is a right circular cylinder that is 0.5 in. diameter and 0.5 in. tall) that is excited by electrons with anywhere between 1 and 662 keV of energy. Thus, the active area must be larger than $\sim 1\,cm^2$ in order to efficiently collect light from the scintillator sample. The response must be linear ($<0.5\%$ deviation is needed) over a dynamic range extending up to ~50,000 incident photons. Single photoelectron resolution is desired, as is high quantum efficiency, as these properties make accurate determination of the luminosity at low (~1 keV) excitation energies possible (see Fig. 1b). The physics of proportionality makes measuring the luminosity at these low energies particularly important, but the low total light output (1 keV of energy deposited in NaI:Tl results in approximately 30 scintillation photons incident on the photodetector) makes accurate measurement particularly challenging.

We evaluate several types of photodetectors for this purpose. Despite their excellent linearity and quantum efficiency, we rule out PIN photodiodes and avalanche photodiodes because their signal-to-noise ratio is inadequate ($1\,cm^2$ area devices are unable to resolve single photoelectrons). We also rule out silicon photomultipliers (SiPMs) [13] as their active area is generally too small and their linearity is usually quite poor over the wide dynamic range required for this application. Thus, we consider three types of photodetector—conventional bialkali PMTs, bialkali PMTs with enhanced quantum efficiency (35–50%, as opposed to 25%) [14,15], and hybrid photodetectors (HPDs) [16–20]. An HPD is similar to a conventional PMT except that the gain is provided not by a dynode structure, but by accelerating the photoelectrons to

* Corresponding author. Tel.: +1 510 486 4432; fax: +1 510 486 4768.
E-mail address: wwmoses@lbl.gov (W.W. Moses).

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~15 keV and then having these electrons deposit their kinetic energy in a silicon PIN diode where the charge is multiplied by impact ionization.

2. Linearity

One advantage of the HPD is that the device is intrinsically very linear. The non-linearities in conventional PMTs arise from the dynode structure, where the "cloud" of multiplied electrons can both alter the current (and thus the voltage and therefore the gain) in the resistor chain that biases the dynode chain and also produce space-charge effects that shield some of the electrons in the cloud (and thus reduce their gain) [21,22]. The HPD does not have this dynode structure and instead is linear as long as the mean ionization energy in silicon remains constant (3.64 eV per e/h pair [23]). In addition, the one-step multiplication process results in much lower gain fluctuations than those in PMTs.

With proper care taken in the dynode design and the biasing circuit, conventional PMTs can also be extremely linear, but it is important to check their performance. We therefore measure the linearity of four conventional PMTs and one PMT with a high quantum efficiency photocathode. The linearity was measured using the apparatus shown in Fig. 2 and a modification of the technique described in [24]. The pulser creates a 10-ns-wide electrical pulse that creates a 20-ns-wide flash of light from either or both of the blue LEDs shown in Fig. 2, and the amount of light produced in each LED is controlled by a resistor. Both LEDs are optically coupled into a 1 in. diameter Lucite sphere that has a 0.25 in. diameter, 2 in. long Lucite rod glued to it. All surfaces of the Lucite sphere and rod are wrapped with white Teflon tape, except for the end of the rod. This Lucite assembly acts as a light mixer/diffuser, and also transports the light emitted by the LEDs through a neutral density filter toward the PMT.

The procedure for measuring the linearity begins by pulsing the upper LED. Throughout the entire procedure, the resistor value for the upper LED is never changed, and so this LED always produces the same amount of light, which we define as one unit of light. The PMT output is recorded by a pulse height analyzer, histogrammed, and the centroid of the distribution computed. The upper LED is turned off, the lower LED is pulsed, and its resistor adjusted until the resulting centroid lies at the same position as when the upper LED was being pulsed. At this point, it is also producing one unit of light (within measurement error, which is

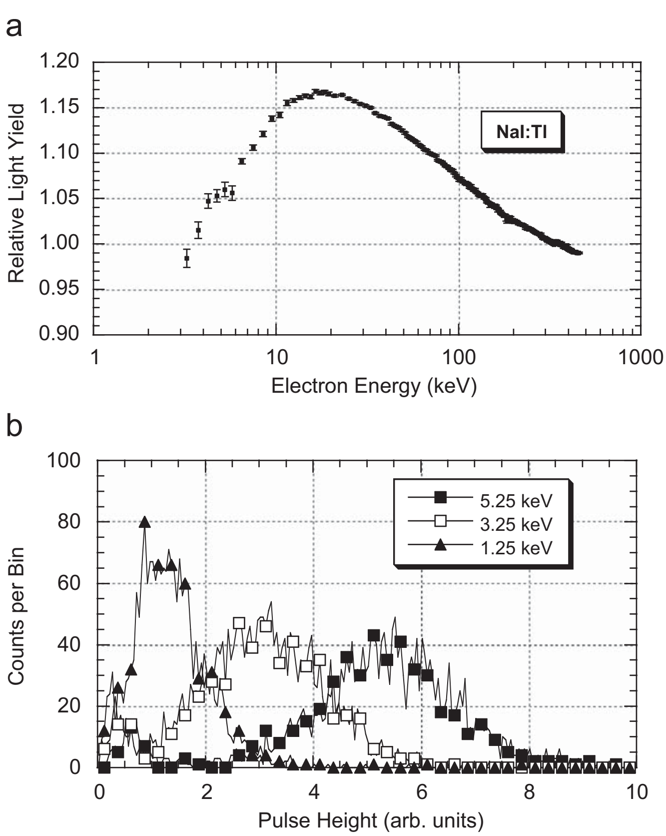

Fig. 1. (a) Plot of the NaI:Tl electron response (light output when excited by electrons, normalized to the value at 444 keV), as measured with a Compton Coincidence device. (b) Raw data used to create some of the individual data points in Fig. 1a. These are histograms of the light output measured by the PMT when the NaI:Tl crystal is excited with 1.25, 3.25, and 5.25 keV electrons.

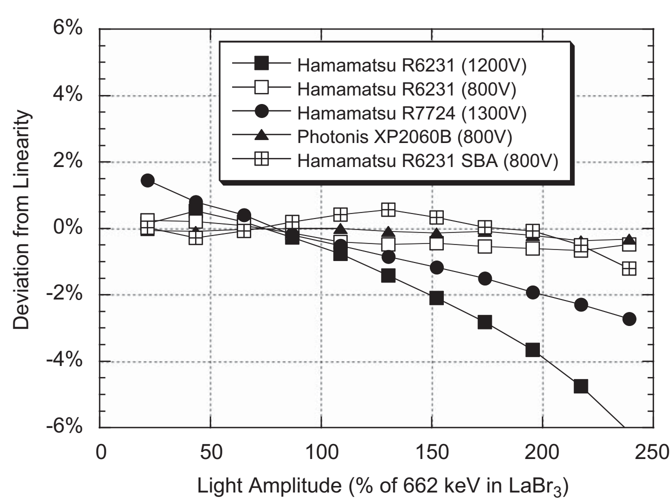

Fig. 3. Plot of the deviation from linearity as a function of light intensity for several photomultiplier tubes.

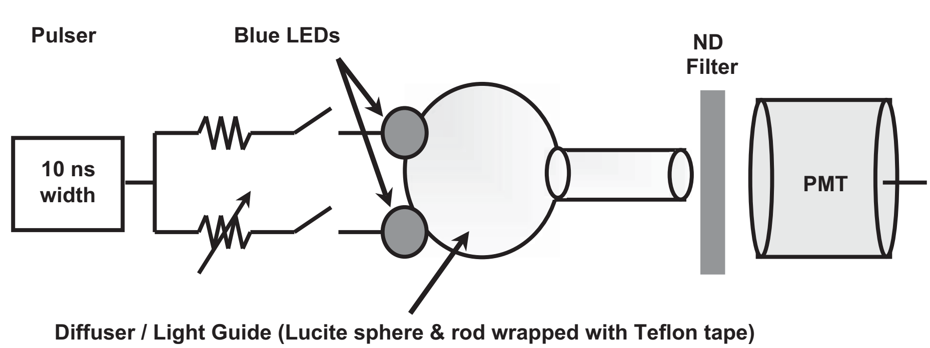

Fig. 2. Diagram of the apparatus used to measure the photomultiplier tube linearity.