

Light Yield, Non-Proportionality, and Emission Characteristics of Scintillator Materials for Silicon Photomultiplier–Based Radiation Detectors

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ABSTRACT

A scintillation detector read out by a silicon photomultiplier (SiPM) is limited primarily by three properties of the scintillator: the number of optical photons generated per unit of absorbed energy (light yield), the constancy of that yield with the energy of the exciting radiation (proportionality), and the wavelength distribution of the emitted light relative to the spectral response of the sensor. This review compiles and cross-checks reported light yields, emission maxima, decay times and densities for the inorganic crystals and polyvinyltoluene plastics most often coupled to SiPMs — NaI(Tl), CsI(Tl), CsI(Na), BGO, LYSO(Ce), GSO(Ce), GAGG(Ce), LaBr₃(Ce), LaCl₃(Ce) and EJ-200 — and states the governing relations for intrinsic yield, energy-resolution decomposition, spectral overlap, microcell saturation and ionization quenching in one consistent notation. Two points distinguish it from material-only surveys. Most tabulated resolutions were obtained with photomultiplier or avalanche-photodiode readout and are systematically better than those achieved with SiPMs, so the comparative tables here keep the two readout classes separate. And the finite microcell count of a SiPM produces a compressive non-linearity that can be mistaken for intrinsic non-proportionality, so the two must be separated experimentally before a material is judged. A worked decomposition of the 662 keV resolution shows that non-proportionality, not photon statistics, dominates in the alkali halides, whereas LaBr₃(Ce) operates close to its statistical limit. The review closes with the selection trade-offs for compact SiPM-coupled instruments and the reporting gaps that currently prevent scintillator–SiPM combinations from being compared on equal terms.

Keywords: scintillator; light yield; non-proportionality; emission spectrum; silicon photomultiplier; photon detection efficiency; energy resolution

INTRODUCTION

A scintillation detector converts energy deposited by ionizing radiation into optical photons, which are then registered by a photosensor [1]. Silicon photomultipliers — dense parallel arrays of Geiger-mode avalanche photodiode microcells — have displaced vacuum photomultiplier tubes (PMTs) in a growing class of compact instruments because they are millimetre-scale, operate at tens rather than thousands of volts, and are immune to magnetic fields [2]. What a SiPM cannot do is recover photons the scintillator never produced, failed to transport to the coupling face, or emitted at wavelengths the sensor detects poorly. To first order, therefore, the energy resolution, linearity and timing of the assembled detector remain properties of the scintillator [1],[3].

Three material properties dominate that contribution. The first is the absolute light yield, which fixes the photon-statistics floor on energy resolution. The second is the proportionality of the yield with the energy of the exciting radiation; departures from proportionality — collectively termed non-proportionality — are now

recognised as the principal cause of energy-resolution degradation in most common scintillators, exceeding the contribution of photon counting statistics [3]–[5]. The third is the emission spectrum, which must overlap the photon-detection-efficiency (PDE) window of the sensor if the generated light is to be converted efficiently into photoelectrons [2].

These properties are normally reviewed independently of the photosensor. That separation is convenient but misleading for SiPM-based design, for two reasons made explicit here. First, the great majority of tabulated “material” light yields and energy resolutions were measured with PMTs or avalanche photodiodes (APDs); replacing the sensor with a SiPM alters the effective quantum efficiency, the excess-noise contribution and the available dynamic range, and the resolutions actually obtained are consistently worse than the tabulated figures. Second, the finite microcell count of a SiPM introduces an instrumental compressive non-linearity that mimics — and in published spectra has been confused with — intrinsic scintillator non-proportionality.

Accordingly, this review (i) compiles and cross-checks light yield, emission maximum, decay time and density for the scintillators most often coupled to SiPMs; (ii) states the quantitative framework — intrinsic yield, resolution decomposition, spectral overlap, microcell saturation and Birks quenching — in a single, dimensionally consistent notation, with worked numbers; (iii) reports PMT/APD-referenced and SiPM-referenced energy resolutions as separate quantities in the comparative tables, which is where much of the apparent disagreement between published values originates; and (iv) identifies the reporting gaps that prevent scintillator–SiPM combinations from being compared on equal terms. The scope is restricted to bulk inorganic single crystals and polyvinyltoluene-based plastics in routine use; scintillating glasses, liquids, gases, ceramics and halide-perovskite emitters lie outside it and are referred to only where they bear directly on the trends discussed.

Scintillation Mechanism and Intrinsic Light Yield

Origin of the light yield and its ceiling

In an inorganic crystal, an incident gamma ray or charged particle creates energetic primary electrons — for gamma rays, through photoelectric absorption, Compton scattering or pair production — which lose energy along their tracks by generating electron–hole pairs and secondary excitations in the host lattice [1]. These carriers migrate, largely non-radiatively, to luminescence centres that are either intrinsic lattice sites or extrinsic activator ions such as Tl^+ in $NaI(Tl)$ or Ce^{3+} in $LYSO(Ce)$ and $GAGG(Ce)$, where radiative recombination produces the scintillation photons [1],[6]. In organic and plastic scintillators the excitation instead resides in the π -electron system of aromatic fluorescent solutes dissolved in a polymer matrix, giving a molecular fluorescence mechanism that is intrinsically faster than the lattice-mediated inorganic process.

The magnitude of the yield follows from a simple energy budget. Creating one thermalized electron–hole pair costs an energy of roughly β times the band gap, so the number of photons produced per MeV of absorbed energy is

$$Y = 10^6 S_t Q / (\beta E_g) \quad (1)$$

where Y is the light yield in photons per MeV, E_g the band gap in eV, β a dimensionless factor of about 2–3 describing the energy cost per electron–hole pair in units of the band gap, S_t the efficiency with which those carriers are transferred to luminescence centres, and Q the quantum efficiency of the centre; both S_t and Q lie between 0 and 1 [6]–[8]. Equation (1) is dimensionally consistent (10^6 eV per MeV divided by an energy per pair) and explains the observed ordering of materials: the ceiling scales inversely with band gap, so wide-gap oxides are intrinsically dimmer than halides.

Taking a gap of about 6 eV, representative of the lanthanum halides, with $\beta \approx 2.5$, Eq. (1) gives an upper bound near 6.7×10^4 photons/MeV; the measured 6.1 – 7.0×10^4 photons/MeV for $LaBr_3(Ce)$ therefore implies that transfer and quenching losses in this material are small. Conversely, the shortfall of BGO relative to its band-gap limit is attributable not to the gap alone but to poor transfer efficiency and to thermal quenching of the Bi^{3+} emission near room temperature.

Reported Values and the Yield–Speed Relationship

Table 1 collects representative values for the materials most relevant to SiPM-coupled design, taken from the primary characterisation studies and reviews cited in its caption. The ranges are not measurement uncertainties: they reflect genuine variation in crystal composition and quality, activator concentration, sample size, surface finish and wrapping, shaping time, and the photosensor used for the calibration. Values quoted for a single sample geometry should therefore be treated as representative rather than absolute, and a material cannot be ranked on light yield alone at the precision of a few per cent. Figure 1 plots the same data as light yield against decay time. Table 1. Representative light yield, peak emission wavelength, principal scintillation decay time, density and hygroscopicity for scintillator materials commonly coupled to SiPMs. Values are literature-derived; ranges span the variation across the cited sources and measurement conditions rather than an experimental uncertainty. Compiled from Refs. [1],[6],[9]–[19].

Material	Light yield ($\times 10^3$ ph/MeV)	Peak emission λ (nm)	Principal decay time	Density (g/cm ³)	Hygroscopic
NaI(Tl)	38–45	415	230 ns	3.67	Yes
CsI(Na)	39–43	420	460 ns (+ μ s tail)	4.51	Yes
CsI(Tl)	52–56	550	680 ns (+ μ s tail)	4.51	Slightly
BGO (Bi ₄ Ge ₃ O ₁₂)	8–9	480	300 ns	7.13	No
LYSO(Ce)	25–32	420	40 ns	7.10	No
GSO(Ce)	8–10	440	30–60 ns	6.71	No
GAGG(Ce)	46–58	520	90 ns (+ slow tail)	6.63	No
LaBr ₃ (Ce)	61–70	380	16–35 ns (Ce-dependent)	5.08	Yes
LaCl ₃ (Ce)	46–49	350	25–28 ns	3.86	Yes
EJ-200 (PVT plastic)	≈ 10	425	2.1 ns	1.02	No

Two entries in Table 1 deserve comment because they are frequently quoted without qualification. The decay time of LaBr₃(Ce) is not a fixed constant: it shortens from about 35 ns at low cerium concentration towards roughly 16 ns in the 5 % Ce compositions used commercially, so quoted values must be read together with the doping level [13],[15]. The upper end of its light-yield range corresponds to Sr²⁺ or Ca²⁺ co-doped material, which reaches about 7×10^4 photons/MeV together with improved proportionality [16]; the same co-doping strategy has since been applied to other halides.

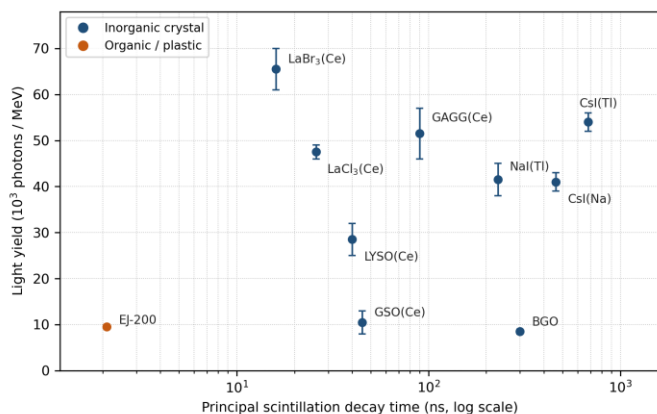


Figure 1. Light yield versus principal scintillation decay time for the materials of Table 1 (original plot; data

compiled from the same sources). Vertical bars indicate the reported yield range, not an experimental uncertainty. The plot separates two families rather than tracing a single trade-off curve: the plastic scintillator EJ-200 is one to two orders of magnitude faster than any inorganic crystal at roughly one sixth of the yield of the brightest of them, while within the inorganic family $\text{LaBr}_3(\text{Ce})$ is simultaneously the brightest and among the fastest.

It is often stated that brightness and speed trade against one another. Figure 1 shows that this is true only within limited groups of materials. Among the activated alkali halides, the long lifetimes of the Tl^+ and Na^+ centres do impose decay times of hundreds of nanoseconds at high yield. But $\text{LaBr}_3(\text{Ce})$ combines the highest yield in the table with a decay time of a few tens of nanoseconds, because the $\text{Ce}^{3+} 5d \rightarrow 4f$ transition is parity- and spin-allowed and the halide host has a small band gap; the same allowed transition makes $\text{LYSO}(\text{Ce})$, $\text{GSO}(\text{Ce})$ and $\text{GAGG}(\text{Ce})$ fast, though at lower yield. The plastic scintillators occupy a separate region of the plane entirely: their nanosecond molecular fluorescence is not in competition with crystal yields but with crystal stopping power. The practical consequence is that the choice between a bright crystal and a fast one is only forced within a material family, and that a genuine trade-off exists at the system level between yield, speed and stopping power rather than between yield and speed alone [9],[10],[19].

Non-Proportionality and Its Contribution To Energy Resolution

Non-proportionality is the dependence of a scintillator's luminous efficiency — photons emitted per unit of deposited energy — on the energy of the exciting radiation, rather than its remaining constant as an idealized scintillator would [3],[4]. Dorenbos, de Haas and van Eijk established through systematic measurements across a wide range of crystals that essentially all common inorganic scintillators are measurably non-proportional, typically showing a depression of relative yield somewhere between a few tens and a few hundred keV with recovery towards higher energies [3]. Because a gamma-ray photopeak is built from many Compton-scattered and photoelectric sub-events distributed over energies below the full-energy value, an energy-dependent yield broadens the photopeak beyond what photon-counting statistics alone would predict [3],[4],[5].

Two experimental routes have quantified the effect. The Compton-coincidence technique used by Valentine, Rooney and co-workers measures the electron response directly and showed that for many alkali halides the non-proportionality term dominates over the statistical term, particularly below a few hundred keV [4],[5]. K-dip spectroscopy, which exploits the abrupt change in the energy of the photoelectron across an absorption edge, extends the electron response to a few keV and has revealed structure that the Compton-coincidence method integrates over [20]. The two methods do not always agree in detail, and part of the spread between published non-proportionality curves for nominally identical materials is methodological rather than physical.

The microscopic origin is now attributed to competition between radiative recombination and non-radiative loss channels — Auger quenching, carrier trapping, exciton–exciton annihilation — whose relative importance depends on the local ionization density along the track [21].

Because ionization density rises as the electron slows, this picture naturally produces an energy-dependent yield. Setyawan and co-workers found a correlation between the degree of non-proportionality and electronic band-structure features such as the band gap and the presence of intermediate states across a broad set of crystal families [22]. That correlation is empirical and has predictive value for screening candidate compositions, but it is not yet a quantitative theory: it does not, for example, account for the improvement produced by aliovalent co-doping at fixed host band structure [16].

Decomposition of the Measured Energy Resolution

The measured relative full width at half maximum of a photopeak is conventionally separated into statistically independent contributions [3],[5]:

$$R^2 = R_{\text{st}}^2 + R_{\text{np}}^2 + R_{\text{inh}}^2 \quad (2)$$

in which R_{st} is the photon-statistics term, R_{np} the contribution of non-proportionality, and R_{inh} the contribution of spatial non-uniformity in light output and light collection. The statistical term is

$$R_{st} = 2.355 (ENF / N_{pe})^{1/2}, \quad N_{pe} = Y E \eta_{coll} PDE_{eff} \quad (3)$$

where N_{pe} is the number of detected photoelectrons (fired microcells) for a deposited energy E , η_{coll} the fraction of generated photons reaching the photosensitive area, PDE_{eff} the spectrally averaged photon-detection efficiency defined in Section 4, and ENF the excess noise factor of the sensor — for a SiPM, the variance of the single-cell charge response inflated by optical crosstalk and afterpulsing [2].

The practical value of Eqs. (2) and (3) is that they allow the non-statistical part of the resolution to be extracted from published measurements. For $LaBr_3(Ce)$, taking $Y = 63 \times 10^3$ photons/MeV at $E = 0.662$ MeV with an illustrative overall collection-and-detection factor $\eta_{coll}PDE_{eff} = 0.25$ and $ENF = 1.2$ gives $N_{pe} \approx 1.0 \times 10^4$ and $R_{st} \approx 2.5$ % FWHM, already close to the 2.6–2.9 % measured with PMT readout [13]: the material operates near its statistical limit and the remaining terms are small.

Repeating the calculation for $NaI(Tl)$ with $Y = 41.5 \times 10^3$ photons/MeV gives $N_{pe} \approx 6.9 \times 10^3$ and $R_{st} \approx 3.1$ %, against a measured resolution of roughly 7 %; the quadratic residual of about 6.3 % is the combined non-proportionality and inhomogeneity contribution. Improving photon collection in $NaI(Tl)$ therefore cannot bring the resolution below about 6 %, whatever the photosensor — the result that motivates treating proportionality, not brightness, as the primary selection criterion for spectroscopy. Figure 2 summarises the qualitative form of the underlying trends.

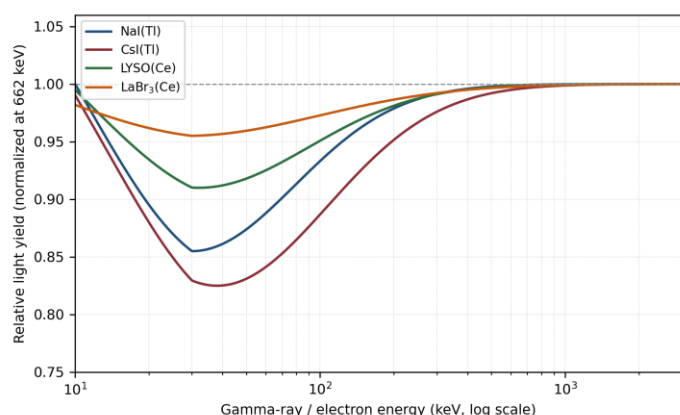


Figure 2. Qualitative illustration of relative light-yield (non-proportionality) trends versus energy, normalized at 662 keV, for $NaI(Tl)$, $CsI(Tl)$, $LYSO(Ce)$ and $LaBr_3(Ce)$. The curves are original schematic renderings of the direction and approximate magnitude of the behaviour reported in Refs. [3],[4],[5],[20],[21]; they are not a digitization of any published dataset and should not be used to read off numerical values.

Comparative Resolution, and Why PMT and Sipm Values Must Be Separated

Empirically, the alkali halides $NaI(Tl)$ and $CsI(Tl)$ show non-proportionality excursions of order 15–20 % between roughly 30 and 1000 keV, corresponding to 662 keV resolutions of about 6–7 % FWHM even though their light yields alone would predict the substantially better statistical limits computed above [3],[4],[5]. $LaBr_3(Ce)$, developed and characterised by van Loef, Dorenbos and co-workers, combines a high yield with excursions of only a few per cent and reaches 2.6–2.9 % FWHM at 662 keV [13]; Sr^{2+} co-doping improves this further, to about 2.0–2.2 %, which remains the best reported for a practical inorganic scintillator [16]. Cerium-doped silicates and garnets occupy an intermediate position, with non-proportionality smaller than the alkali halides but larger than $LaBr_3(Ce)$ [23]. The best $GAGG(Ce)$ figures — 4.2 % at 662 keV for optimized Ga content, measured with APD readout — show that the material's intrinsic resolution is good, and that the poorer values commonly quoted reflect the readout rather than the crystal [12].

That last point generalises, and it is the main reason published resolutions for the same material disagree. Coupling a crystal to a SiPM instead of a PMT changes three things at once: the spectrally weighted detection efficiency, the excess noise factor, and the dynamic range. Measured side by side on the same $\text{LaBr}_3(\text{Ce})$ crystal, a 4×4 SiPM array gave 4.0 % FWHM at 662 keV where a PMT gave 3.0 % [24]. For $\text{GAGG}(\text{Ce})$ on a single $3 \times 3 \text{ mm}^2$ SiPM, 10.2 % was measured, rising to 10.5 % once the microcell saturation correction of Section 4.3 was applied [25] — a factor of about two worse than the best APD-referenced value for the same material. With careful design the penalty can be made small: large-area $\text{LaBr}_3(\text{Ce})$ detectors read out by SiPM arrays have reached about 3 % at 662 keV, comparable with PMT readout [26]. Table 2 therefore reports the two readout classes in separate columns; merging them, as is common in materials tables, produces ranges so wide that they cannot inform a design decision.

Table 2. Non-proportionality and reported 662 keV energy resolution for selected scintillators, separated by readout class. Literature-derived values; the SiPM column reports specific published crystal–sensor combinations and is not a material constant. An em dash indicates that no directly comparable published value was identified. Compiled from Refs. [3]–[5],[12],[13],[16],[23]–[26].

Material	Non-proportionality excursion	$\Delta E/E$ @ 662 keV, PMT/APD readout	$\Delta E/E$ @ 662 keV, reported SiPM readout	Dominant limiting factor
$\text{NaI}(\text{Tl})$	Large (~15–20 %)	~6.5–7 %	—	Non-proportionality
$\text{CsI}(\text{Tl})$	Large (~15–20 %)	~6–7 %	—	Non-proportionality
$\text{LYSO}(\text{Ce})$	Moderate	~7–9 %	—	Non-proportionality and light collection
$\text{GAGG}(\text{Ce})$	Moderate	4.2–4.9 % (best reported)	~9.4–10.5 %	Readout: PDE, excess noise, microcell saturation
$\text{LaBr}_3(\text{Ce})$	Small (a few %)	2.6–2.9 %; 2.0–2.2 % with Sr co-doping	3–4 %	Photon statistics (near-ideal)
$\text{LaCl}_3(\text{Ce})$	Small to moderate	~3.3–4 %	—	Photon statistics and non-proportionality

Emission Spectra, Spectral Matching and Optical Coupling

Effective photon detection efficiency

Total photon yield and proportionality are necessary but not sufficient: what reaches the readout is the overlap integral of the emission spectrum with the sensor response. The relevant figure of merit is the spectrally averaged detection efficiency

$$\text{PDE}_{\text{eff}} = \int \varphi(\lambda) \text{PDE}(\lambda) d\lambda / \int \varphi(\lambda) d\lambda \quad (4)$$

where $\varphi(\lambda)$ is the scintillator emission spectrum and $\text{PDE}(\lambda)$ the wavelength-dependent photon detection efficiency of the SiPM at the chosen overvoltage [2]. Both integrals run over the sensor's sensitive range. Equation (4) is the quantity that enters Eq. (3); a single number quoted as “the PDE” of a device, normally its peak value, will overestimate N_{pe} whenever the emission maximum is displaced from the PDE maximum.

Standard silicon SiPMs reach peak PDE in the blue, near 420–450 nm, and retain a substantial fraction of that peak across the green, while near-ultraviolet-enhanced devices shift the maximum towards 380–420 nm through thinner entrance layers and modified antireflection coatings [2]. Figure 3 places the emission maxima of Table 1 against these regions.

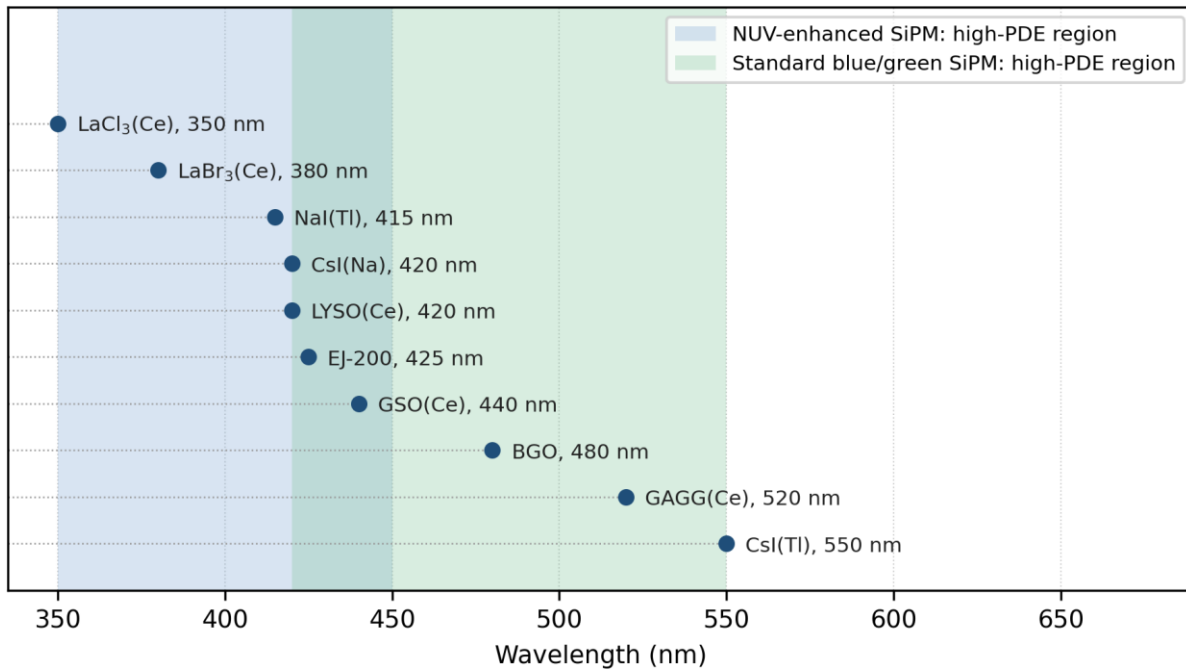


Figure 3. Emission maxima of the scintillators of Table 1 (verified literature values) shown against the approximate high-PDE regions of standard blue/green-sensitive and near-ultraviolet-enhanced SiPMs. Original schematic: the shaded bands indicate typical wavelength ranges of high sensitivity as described in Ref. [2] and are not digitized PDE curves for any specific device. Device-specific PDE data should be taken from the manufacturer for the sensor and overvoltage actually used.

The common statement that CsI(Tl), emitting at 550 nm, is poorly matched to SiPMs requires correction. Bialkali PMT quantum efficiency falls steeply beyond about 500 nm, which is the historical origin of the concern; silicon does not behave this way, and standard SiPMs retain useful efficiency through the green and into the red. CsI(Tl) is consequently one of the combinations that benefits from the change of sensor rather than suffering from it, and the same holds for GAGG(Ce) at 520 nm. The genuine mismatch lies at the other end of the range: LaBr₃(Ce) at 380 nm and especially LaCl₃(Ce) at 350 nm emit where standard SiPM response is falling and where absorption in the protective window and encapsulation becomes significant, so these materials benefit disproportionately from NUV-optimized devices [2],[26]. Selecting a scintillator without the PDE curve of the specific sensor and overvoltage in hand is therefore not a meaningful exercise.

Optical Coupling and Light Collection

The collection factor η in Eq. (3) is set by refractive-index matching, surface finish, reflector choice and, for SiPMs in particular, by area matching. Inorganic scintillators have high refractive indices — approximately 1.85 for NaI(Tl), 1.81 for LYSO(Ce) and 2.15 for BGO — against about 1.4–1.46 for silicone greases and optical pads and about 1.5 for typical sensor encapsulants [1]. For a crystal of index 1.81 coupled through a medium of index 1.41, the critical angle is about 51°, so only some 19 % of isotropically emitted light falls within the escape cone at first incidence; the remainder must be recovered by multiple reflections from a diffuse or specular wrapping. Coupling a plastic scintillator (index 1.58) is correspondingly easier, and this partly offsets its lower intrinsic yield. Air gaps are strongly penalised and should be eliminated.

Area matching is the specifically SiPM-related constraint. A 3×3 mm² device on a crystal face of 10×10 mm² intercepts a small fraction of the light arriving at that face, and the shortfall appears directly as a reduced photoelectron count in Eq. (3). Tiled arrays, light guides and monolithic large-area devices all address this, at the cost of increased capacitance, slower signals and higher aggregate dark count rate. Diffusive interfaces introduced by encapsulation can also degrade position reconstruction in monolithic crystals [24]. Emission spectrum, sensor PDE, coupling-medium transmission, reflector and sensor area must therefore be optimized jointly rather than chosen independently.

Microcell Saturation and Other Sensor-Induced Non-Linearity

A SiPM contains a finite number of microcells, and a cell that has fired cannot respond again until it has recharged. If the scintillation pulse is short compared with the microcell recovery time, the number of fired cells is

$$N_{\text{fired}} = N_{\text{cell}} [1 - \exp(-N_{\text{pe}} / N_{\text{cell}})] \quad (5)$$

with N_{cell} the total microcell count [2]. The response is linear only while $N_{\text{pe}} \ll N_{\text{cell}}$; beyond that it compresses, and the compression grows with deposited energy. For scintillators slower than the microcell recovery time the effective dynamic range is larger than Eq. (5) implies, because cells recycle during the pulse, which is one of the few respects in which a long decay time is an advantage.

The consequence for the subject of this review is direct: microcell saturation produces a deficit of signal at high energy, whereas intrinsic non-proportionality in most inorganic scintillators produces a deficit at low energy. The two have opposite signs and can in principle be separated, but only if the saturation correction is applied before the material is characterised. Seitz and co-workers observed and corrected exactly this behaviour for GAGG(Ce) on a $3 \times 3 \text{ mm}^2$ device, where the 662 keV point deviated visibly from a linear response fit to lower energies [25]. Published detector non-linearity curves that omit this correction cannot be interpreted as material non-proportionality.

Two further sensor properties bear on achievable resolution and are absent from conventional materials tables. Correlated noise — optical crosstalk between microcells and afterpulsing — inflates the ENF in Eq. (3) and increases with overvoltage, so the overvoltage that maximises PDE is generally not the one that minimises resolution. And the SiPM breakdown voltage drifts with temperature by tens of millivolts per degree, so that without compensation the gain drift over a modest ambient excursion degrades the photopeak width by more than the difference between two candidate scintillators; temperature-compensated bias is a prerequisite for any comparison of materials on a SiPM [26].

In space and accelerator environments, displacement damage progressively raises the dark count rate and the effective low-energy threshold, which constrains material choice indirectly by raising the light yield needed to stay above threshold [24].

Organic, Plastic and High-Z-Loaded Scintillators

Where fast timing rather than energy resolution governs the design, polyvinyltoluene-based plastics such as

EJ-200 remain the material of choice: a principal decay time near 2 ns is one to two orders of magnitude shorter than that of any common inorganic crystal, at a light yield roughly one sixth that of the brightest crystals [17]. Their low effective atomic number and density of about 1.02 g/cm^3 give poor photoelectric efficiency, restricting their principal use to charged-particle detection, fast-neutron detection through recoil protons, and time-of-flight applications where speed and cost outweigh full-energy-peak efficiency [17],[19].

Plastics are largely insensitive to non-proportionality in the sense discussed in Section 3, because their response to the minimum-ionizing electrons produced by gamma interactions is close to linear. Their dominant non-linearity is ionization quenching, described empirically by Birks' law:

$$dL/dx = S_B (dE/dx) / [1 + kB (dE/dx)] \quad (6)$$

where dL/dx is the light emitted per unit path length, dE/dx the stopping power, S_B the absolute scintillation efficiency, and kB the Birks coefficient, conventionally treated as a single fitted parameter with units of length per unit energy [27]. Quenching becomes significant only where dE/dx is large, so Eq. (6) governs the response to protons, alphas and heavy recoils — and hence the light-output calibration of fast-neutron detectors and the neutron/gamma discrimination boundary — rather than the response to Compton electrons.

The recognised weakness of plastics, poor gamma stopping power, has motivated sustained work on high-Z loading, in which organometallic compounds of lead, bismuth or hafnium are dissolved in the polymer to raise the photoelectric fraction.

Hajagos and co-workers review the state of this field and the recurring difficulty: loading that is heavy enough to give a useful photopeak generally reduces light yield and optical transparency and can introduce self-absorption and long-term stability problems, so that gains in stopping power are partly returned as losses in resolution [28]. High-Z-loaded plastics are best regarded as an active research direction rather than an established alternative to crystals for spectroscopy.

Ionization quenching is not exclusive to organics, and this is where Sections 3 and 5 connect. A Birks coefficient of about 0.075 mm/MeV has been derived for GAGG(Ce) from measurements in a 20–80 keV X-ray beam, a value large compared with most high-Z inorganic scintillators, and large enough to produce measurable changes in both gain and energy resolution across the K-edge of a constituent heavy element [29]. Part of what is conventionally reported as low-energy non-proportionality in this material is therefore describable by Eq. (6), and materials intended for hard X-ray spectrometry or polarimetry should be characterised with this in mind.

Material Selection for a SiPM-Coupled Detector

Drawing Sections 2–5 together, five criteria govern the choice, in roughly this order of leverage. Non-proportionality sets the resolution floor that no amount of photon collection can beat, and separates materials that can approach their statistical limit — LaBr₃(Ce), LaCl₃(Ce) — from those that cannot [3],[4],[13]. Light yield then determines how closely that floor is approached, through Eq. (3). Spectral overlap with the specific sensor discounts the usable yield through Eq. (4) and must be evaluated against a real PDE curve, not a nominal peak value.

Decay time sets the timing resolution and count-rate ceiling and, through Eq. (5), interacts with the available dynamic range. Finally, practical factors — hygroscopicity and the hermetic packaging it forces, intrinsic radioactivity, mechanical robustness, availability and cost — often decide the outcome for a portable instrument even when they are absent from performance tables.

The ¹⁷⁶Lu activity of LYSO(Ce) and the ¹³⁸La activity of the lanthanum halides matter wherever low background is required, and both are properties of the material rather than of the detector design [11],[13]. Table 3 condenses these considerations into guidance organised by design driver.

Table 3. Material-selection guidance for compact SiPM-coupled detectors, synthesized from the properties and limitations discussed in Sections 2–5. The recommendation is conditional on the stated design driver; no material is preferable on all criteria simultaneously.

Primary design driver	Preferred material(s)	Basis	Principal caveat
Best achievable energy resolution	LaBr ₃ (Ce), LaBr ₃ (Ce,Sr)	Highest light yield combined with the smallest non-proportionality of the practical crystals	Hygroscopic, requiring hermetic packaging; ¹³⁸ La internal background; high cost; near-UV emission favours NUV-enhanced SiPMs
Compact, rugged general-purpose spectroscopy	GAGG(Ce), LYSO(Ce)	Non-hygroscopic, dense, emission well inside the standard SiPM high-PDE region	Moderate non-proportionality; GAGG slow decay component and significant Birks quenching below ~30 keV; ¹⁷⁶ Lu background in LYSO

Sub-nanosecond timing or high rate	EJ-200 (plastic); LYSO(Ce) where stopping power is also needed	2 ns and 40 ns decay times respectively; plastic couples easily and is inexpensive at large area	Plastic has negligible photopeak efficiency; both require attention to microcell saturation because the light is fast relative to cell recovery
Low-cost, large-volume gamma counting	NaI(Tl), CsI(Tl)	Mature, inexpensive, high yield; CsI(Tl) is only slightly hygroscopic and its 550 nm emission suits silicon better than bialkali PMTs	Non-proportionality caps resolution near 6–7 % regardless of readout; long decay limits count rate; NaI(Tl) is hygroscopic
High density at low cost, resolution secondary	BGO	Density 7.13 g/cm ³ and high effective atomic number; non-hygroscopic and mechanically robust	Low light yield ($\sim 9 \times 10^3$ ph/MeV) and pronounced temperature dependence of the yield near room temperature

Limitations, Open Questions and Research Gaps

The first limitation is **inconsistent reporting**. Light yields and energy resolutions are often reported without sufficient information on crystal dimensions, surface finish, wrapping, activator concentration, shaping time, and photosensor, although these factors can affect the measured performance by amounts comparable to differences between materials. The ranges in Table 1 illustrate this problem. A minimum reporting standard for scintillator characterization would improve comparability more effectively than further measurements of already well-studied materials.

Second, non-proportionality remains method-dependent. Compton-coincidence and K-dip measurements probe different electron-energy ranges and have different systematic effects, while gamma-referenced measurements also depend on the interaction-type distribution [4],[20]. Consequently, reported curves for the same material can differ by several percent in excursion depth, limiting precise ranking based on proportionality alone.

Third, the underlying theory remains incomplete. Band-structure descriptors provide useful screening criteria but do not reliably predict the magnitude of non-proportionality for new compositions or explain why aliovalent co-doping can improve proportionality with little change in the host band structure [16],[22]. A predictive framework linking track structure, carrier thermalization, and trap populations to the measured electron response remains an important open problem.

Fourth, and most directly relevant to this review, there is no systematic benchmark dataset for scintillator–SiPM combinations. Published results generally involve particular crystals, sensor types, overvoltages, and temperatures, with saturation corrections applied inconsistently or not reported. Consequently, the SiPM-referenced comparison in Table 2 remains sparse. A controlled benchmark using several scintillators and SiPM types under a common protocol, including saturation correction and documented temperature compensation, would substantially improve material selection for SiPM-based detectors. Finally, several factors that limit deployed instruments are not captured in conventional material-property tables, including temperature-dependent scintillator yield, SiPM gain and dark-count rate, radiation-induced degradation, and long-term stability of encapsulation and optical coupling. Although medical imaging and time-of-flight applications continue to drive the development of brighter and faster scintillators [30], the performance of compact SiPM-based instruments is increasingly determined by the combined effects of material, sensor, environmental, and readout-system properties.

CONCLUSIONS

Light yield, proportionality, and emission wavelength jointly determine how effectively a scintillator can be exploited with a SiPM, but their contributions are not equal. The resolution analysis shows that, for common alkali halides, non-proportionality contributes more strongly than photon statistics, whereas LaBr₃(Ce),

particularly with Sr co-doping, approaches its statistical limit at the cost of hygroscopicity, internal radioactivity, and higher cost. Garnet and silicate scintillators provide a practical compromise for compact detectors because of their non-hygroscopic nature and good spectral compatibility with standard SiPMs. For SiPM-based detectors, **spectral matching, microcell saturation, and readout configuration** are particularly important. Spectral compatibility should be assessed using the overlap of the scintillation spectrum with the actual SiPM PDE curve rather than peak wavelengths alone. Microcell saturation introduces a compressive non-linearity that must be separated from intrinsic scintillator non-proportionality, while the choice of SiPM and readout can significantly affect the measured energy resolution. A standardized characterization protocol covering crystal, SiPM, operating conditions, temperature, and saturation correction would enable more meaningful comparison of scintillator–SiPM combinations and guide reliable material selection.

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