Scintillation and luminescence in transparent colorless single and polycrystalline bulk ceramic ZnS

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Abstract:

ZnS:Ag is a well-known, extremely bright scintillator used in powder form for α -particle detection and, mixed with powdered LiF, for thermal neutron detection. Recently, we discovered some colorless and transparent commercial bulk single-crystal and polycrystalline (chemical vapor-deposited) ZnS forms that scintillate in response to α -particles. The scintillation light transmits through the sample thickness (millimeters), challenging the commonly held assumption that ZnS is opaque to its own scintillation light. Individual α -particle events were imaged in space and time using a charged-particle camera originally developed for medical imaging applications. Photoluminescence (PL) and PL excitation show that scintillating bulk ZnS likely depends on different electronic defects than commercial ZnS powder scintillators. These defects, associated with copper and oxygen, are discussed in relation to PL results and extensive literature assessment. Commercial transparent ZnS is routinely produced by chemical vapor deposition to sizes larger than square meters, enabling potentially novel radiation detection applications requiring large, thick apertures.

Key Words:

ZnS, alpha particle scintillator, photoluminescence, phosphor

1 Introduction

ZnS is perhaps the most ubiquitous phosphor, having been known for over 100 years. Additionally, ZnS is the brightest known scintillator, $\sim 95,000$ ph/MeV [1]. ZnS scintillator is conventionally made by adding AgNO_3 and NH_4Cl to make ZnS:Ag,Cl resulting in blue emission (2.80 eV, 450 nm) [2] with a decay time of 5 ns (γ -ray) to 100 ns (α -particle) [3]. It is generally believed that ZnS:Ag scintillator is only suitable for α -particle sensing because commercial powders scatter the emission light in thicknesses greater than ~ 100 μm [4]. Additionally, $^6\text{LiF/ZnS:Ag}$ is used in thin opaque screens for thermal neutron detection with good gamma rejection [5-8], a technology with origins from 1960 [3]. Thermal neutrons interact with the ^6Li via the $^6\text{Li}(n,\alpha)^3\text{H}$ reaction, and the resultant charged particles produce light in the ZnS. Recently, ZnS has been combined with $^{10}\text{B}_2\text{O}_3$ in screens [9] or as a borate glass [10] to detect thermal neutrons using the $^{10}\text{B}(n,\alpha)^7\text{Li}$ reaction. ZnS is also a wide-bandgap semiconductor, and in the process of attempting to attain p-type doping, lithium defect chemistry and electronic and optical effects have been investigated [11], but never for the express purpose of neutron detection. ZnS:Ag has, however, been considered for fast neutron detection [12], using recoil protons produced by fast neutrons in a hydrogenous material; again a technology at least 50 years old [3].

In parallel to research for luminescent applications, ZnS was developed as a bulk ceramic material by chemical vapor deposition (CVD) for military infrared windows starting in the early 1970s [13]. By the 1980s, processes had been developed to make fully transparent and colorless bulk CVD ZnS through the method of hot-isostatic pressing (HIP) [14]. Despite long interest for radiation detection, little research has been conducted on the fundamental mechanisms of light output in doped ZnS since basic television-phosphor work in the 1960s (e.g., [15]). Photoluminescence and cathodoluminescence in nominally undoped polycrystalline CVD ZnS has been investigated recently [16,17]. This work concluded that luminescence in CVD ZnS is primarily due to transitions involving isoelectronic oxygen complexes (ZnS:O) and not transition metal impurities.

Based on this knowledge, as well as the reports of scintillation in transparent polycrystalline II-VI materials with isoelectronic defects, such as ZnS:Te [18] and ZnSe:Te [19], and the extremely fast scintillation reported in ZnO materials [20,21], we resolved to test the scintillation behavior of a wide range of ZnS materials (~ 50) available to us [22], including single crystals, CVD materials, and silver-doped materials, using a very fast optical camera under development for medical imaging [23]. About 15% of these optically transparent materials scintillated when exposed to α -particles, transmitted the light through the thickness of the solid sample (1-7 mm) and had individual scintillation events that could be imaged in space and time. The following sections describe representative scintillating materials and further investigation into their properties as assessed by spectral photoluminescence measurements.

2 Experimental

A number of previously available bulk ZnS samples [22,24] were tested for scintillation using an alpha source and the time-resolved spatial imaging camera described below. Samples were tested on both sides of the disks with the α -particles directly in contact with the samples. Some of the strongly scintillating samples were further analyzed by photoluminescence methods. Strongly scintillating samples included single crystals (sample M), commercial CVD-HIP samples (samples V, P), specially prepared CVD-HIP samples (sample F), and hot-pressed opaque ZnS (sample K). The single crystal ZnS sample was a 1-mm-thick square with sides of 10 mm, and the CVD ZnS samples were 25 mm in diameter and 3 – 5 mm thick. Additionally, commercially available ZnS (Eljen Technology, EJ-440) (sample N) and LiF/ZnS:Ag phosphor screens (Eljen Technology, EJ-426) (sample S) were measured for comparison. The ZnS:Ag and LiF/ZnS:Ag commercial powder screens were ~ 250 to 500 μm thick. These screens are typically produced by embedding ZnS and LiF powders in a polymer matrix; the EJ-426 includes LiF for thermal neutron sensitivity [6]. In this paper, detailed luminescence data are shown for the three CVD samples and powder phosphor screens.

The discovery of a scintillation response on samples of thick, polycrystalline ZnS was made using a single-event, radiation-imaging camera called iQID (ionizing-radiation Quantum Imaging Detector) [23]. iQID combines an image intensifier, coupling optics, and a CCD/CMOS camera for high-resolution imaging. A scintillator is placed in contact with the image intensifier's fiber-optic entrance window. Scintillation light is amplified by the intensifier at optical gains ranging from 10^4 - 10^6 . The amplified light is imaged onto a CCD/CMOS camera that streams images at fast frame rates or short exposure times sufficient for single-event detection. The light distribution produced by the scintillation event is finely sampled by camera pixels, which are then used to precisely estimate the 2-D or 3-D location of the charged-particle interaction [23]. Multiple events may be present in an image frame and can be individually identified if their light distributions do not significantly overlap. The iQID imaging method with thick, polycrystalline ZnS using an alpha source is illustrated in Figure 1.

To compare the relative brightness between ZnS:Ag commercial powder screens and a scintillating CVD ZnS sample, both scintillators were coupled to a 25-mm diameter Bialkali photomultiplier (PMT) tube (Hamamatsu R1924A and E2924-500), pulse waveforms were acquired, and pulse-height spectra were generated. A 4 MeV alpha source (^{239}Pu) was placed approximately 10 mm above the ZnS sample for uniform illumination of the entire CVD sample. Acquisition time for the pulse-height spectrum histogram was 24 hours for the CVD ZnS and 48 hours for the commercial screen (EJ-440). The data shown are not background-subtracted, but have a high threshold setting that greatly reduces background contributions.

The photoluminescence excitation (PLE) and emission (PL) spectra were recorded on a spectrofluorometer (Horiba Jobin Yvon fluorolog-3). PLE spectra were obtained by monitoring the 522-nm emission band. For photoluminescence emission spectra, excitation wavelengths of 290, 340, and 360 nm were selected from a broadband xenon lamp source and a monochromator. The emitted light was detected using a Hamamatsu R928 PMT in the range of 350 – 950 nm.

3 Results

3.1 Alpha particle scintillation

Scintillation results are summarized in Table 1, emphasizing the non-uniform behavior. In order to obtain relative brightness of the commercial ZnS powder screens and the test samples, the commercial screens (with transparent substrates) were placed directly on top of the test sample that was in contact with the iQID camera or PMT. In this way the scintillation light from the powder screen (sample N) had to transmit through the thickness of the test sample (sample F). The powder screen was then removed and the test sample was exposed to the alpha source under the same conditions (distance to the source and settings on the camera or PMT electronics). Thus, relative brightness can be estimated from the images or pulse height spectra collected. iQID images of events from both configurations are shown in Figure 2. For very thin samples, the spatial extent of the recorded alpha event is quite small relative to that shown in Figure 2, which represents a refraction of the light as it travels to the back side where it is detected. Still images of other scintillating samples are shown in Figure 3 (a and b), while representative full movies showing the time-extent of the events can be found in the supplementary information online. Shown in Figure 3c and 3d are images of the inhomogeneity of the scintillation in some CVD samples (upper left area of the disk was “active”), and the common origin of centers responsible for both scintillation and fluorescence. Finally, some samples had defects that showed long-lived fluorescence under ultraviolet light, clearly visible using a standard camera (Figure 3e).

The pulse-height comparison between ZnS:Ag commercial powder screen and scintillating Sample F, using the alpha source and PMT, shows a comparable mean brightness (Figure 4). The CVD ZnS sample has better resolution and two peaks.

3.2 Photoluminescence results

PLE spectra generally show a peak at 340 nm for the 522 nm emission, while PL generally shows varying amounts of two peaks, one in the blue (~450 nm) and one in the green (~522 nm). When the same sample was probed in different spots, the emission intensities often appeared interchanged (blue vs. green) due to inhomogeneity. In the instances where one region showed scintillation but another did not, the same was true for photoluminescence. For instance, excitation at 340 nm produced the highest light output, but occasionally 360 nm excitation produced some output.

- **Sample F:** (Figure 5). Sample is inhomogeneous in that some spots and one complete side of the sample produce no PL. For “active” spots, excitation at 340 nm produces PL, while excitation at 360 nm is inconsistent, in one case producing no PL and in another case producing mostly blue PL (Figure 5b). PL intensity is stronger in the blue 450 nm peak than the green 522 nm peak in all cases where 340 nm excitation is used, but both emissions are clearly present and an 850-nm PL is observed (Figure 5b). PLE shows a peak for the 522-nm emission, the only emission measured for PLE (Figure 5a).
- **Sample P:** (Figure 6). Excitation at 290 nm produces no PL (not shown); excitation at 340 nm produces clear PL; excitation at 360 nm is inconsistent (in one case producing no PL and in the other weak PL); PL intensity is stronger in the green than in the blue in all cases, and the blue emission is barely evident (Figure 6b). PLE also is inconsistent, in one case peaking only for the 522-nm (green) emission and not for the 450-nm (blue) emission (Figure 6a); in the other case, weak PLE peaks were observed for emissions at 412 nm, 437 nm, 522 nm, and 590 nm (not shown).
- **Sample V:** (Figure 7). Excitation at 290 nm produces no PL (not shown); excitation at 340 nm produces clear PL; excitation at 360 nm produces very weak PL (not shown); PL intensities of blue and green are nearly equal, and in one case the blue peak was larger than green, while in the other case the green peak was somewhat larger (Figure 7b). No 850-nm peak is evident. In contrast, PLE shows a strong peak at ~340 nm for both 443-nm and 522-nm emissions (Figure 7a). The non-scintillating side shows some weak PL in blue, green, and 850 nm when excited with 340 nm light, and the PLE shows a peak at 340 nm in response to a 522-nm emission (not shown).
- **Sample S:** (Figure 8). PLE data showed that no emission at 400 nm was observed with excitations up to 360 nm, a broad excitation from ~260 to 410 nm was observed for the 480-nm emission, and no excitation was observed in response to the 540-nm emission (Figure 8a); it is apparent that the PL at 480 nm can be broadly excited in this sample. Note that the shape of the excitation is quite broad—very different than the sharp excitation of the CVD samples. PL is nearly Gaussian and centered on 450 nm, with different excitation wavelengths producing somewhat different intensities but no spectral changes (Figure 8b).

Direct comparisons of the luminescence results for all the scintillating ZnS samples are shown in Figure 9. The PLE comparison is shown for green luminescence: 540 nm for ZnS screen and 522 nm for CVD ZnS (Figure 9a). The PLE comparison for the blue luminescence (not shown), 480 nm for ZnS screen and 450 nm for CVD sample V, is similar to that obtained for the green luminescence. The PLE for the green emission in the powder screen is quite broad, but has a peak about the same wavelength as the other samples (~340 nm as seen in Figure 9a). It is believed that the broad excitation of the powder screen is due to the polyester backing sheets(s) (EJ-426 HD2) and/or polymer vehicle for the powder [25]. The PL comparison, taken with excitation at 340 nm (342 nm for sample S), shows that the blue emission of the screen (sample S) is similar to the blue emission in the CVD samples. Blue/green intensity decreases progressively going from sample S to F to V to P. Maximum intensity in the blue is found at 446-449 nm (Figure 9b).

4 Discussion

4.1 Luminescence in ZnS

Due to its large band gap of ~ 3.7 eV, ZnS is a very effective medium for phosphors (e.g., ZnS:Cu) [26], α -particle scintillators (e.g., ZnS:Ag) [27] and lasers (e.g., ZnS:Cr) [28]. Much is known about the luminescence of mass-produced ZnS for powder phosphors [2], but surprisingly little has been published on the electronic defects in CVD ZnS (with a few notable exceptions [29-31]), which is produced as bulk optics for its infrared transparency. Both Ag-activated (e.g., ZnS:Ag,Cl) and “self-activated” (e.g., ZnS:Cl, where Cl is an impurity from the crystal growth flux) ZnS produce a blue luminescence. The blue luminescence in ZnS has always been called the “self-activated” (SA) luminescence unless a metal activator, such as silver or copper, is specifically added. However, SA luminescence in CVD ZnS has a totally different character.

Impurities are measurably present, even in pure semiconductors, in the range of 10^{14} - $10^{15}/\text{cm}^3$ and give rise to bound excitons [32,33]. Estimates from compiled glow discharge mass spectrometry data show 0.1-0.5 ppmwt copper (~ 0.39 ppma or $\sim 10^{18}/\text{cm}^3$) in typical CVD ZnS [22], most likely impurities from zinc raw material, which is more than enough to account for any observed PL emissions related to copper defects. Oxygen is thought to be ubiquitous in as-prepared ZnS made by any method not involving prolonged treatment by annealing in sulfur vapors. Morozova et al. [34] claim that oxygen is present in ZnS in concentrations greater than $10^{18}/\text{cm}^3$, but more frequently 10^{19} to $10^{20}/\text{cm}^3$, and this has been verified recently for various commercially available CVD ZnS materials [35]. It should be noted that “determinations of dissolved oxygen by x-ray structural analysis and by means of the total amount of dissolved oxygen in ZnS through activation or chemical analyses has shown that, in many cases, $[\text{O}]_{\text{tot}}$ is 2-3 times greater than the density of dissolved oxygen $[\text{O}_\text{s}]$ ” [34]. Oxygen has been shown to have an effect on the luminescence of transition metals such as silver. It has been argued that the perceived optical effect of other dopants on the luminescence is *not* due to the optical activity of that dopant (such as silver or chlorine), but rather the effect of that dopant *on the distribution of oxygen* [34].

Oxygen has numerous complicated effects on luminescence in ZnS. Its presence has been shown to give rise to blue (SA) luminescence in the absence of deliberately added activators and co-activators. One model of luminescence in ZnS has presented which incorporates the effect of oxygen doping on copper luminescence, and proposes a deep activator complex that can take multiple charge states composed of a single isoelectronic oxygen atom and a zinc atom moved off its lattice site towards the oxygen [16,30,36-38]. In this model [36], the main blue, green, and red bands in HIP CVD polycrystalline ZnS and single-crystal ZnS can be attributed to defects associated with oxygen plus a transition metal (normally copper but could be silver, excess zinc, or others). The defect complex is described as an isoelectronic oxygen defect (O_s) locally associated with a zinc interstitial (Zn_i) and zinc vacancy (V_Zn), which represents a shift of the position of the zinc atom due to lattice strain compensation near the oxygen substitutional atom [36]. This acceptor defect complex can take three charge states, which are named SA(I), $\{\text{O}_\text{s}-\text{Zn}_\text{i}^+-\text{V}_\text{Zn}''\}'$, SAL(II), $\{\text{O}_\text{s}-\text{Zn}_\text{i}^{2+}-\text{V}_\text{Zn}''' \}^x$, and (III), $\{\text{O}_\text{s}-\text{Zn}_\text{i}^{2+}-\text{V}_\text{Zn}' \}'$, where SA indicates “self-activated” and SAL is SA luminescence, with characteristic emission bands in the blue, ultraviolet, and green, respectively [36]. In each case the activator is the singly or doubly negatively charged defect V_Zn or Cu_Zn , and the co-activator is singly or doubly positively charged interstitial Zn_i or Cu_i . [39]. In ZnS, the copper-blue luminescence can be explained as the Cu(I) defect, analogous to SA(I). Substitutional copper in zinc sites favors the introduction of oxygen. Even though the III and Cu(III) have almost identical luminescence wavelengths in the green, the copper-doped green phosphor is more widely used due to the somewhat increased stability of the center, due to copper-induced lattice strain and local oxygen volume compensation [39].

It is thus extremely likely that copper and oxygen impurities are critical for producing optically active defects in undoped CVD ZnS. Thermoluminescence and x-ray (45-keV) excitation measurements of doped Zn(S,Se) solid solutions showed that copper-doped, and not silver-doped, materials exhibited bright outputs [40]. Self-activated blue luminescence spectra from Zn(S,O_s) solid solutions is very similar to those of silver and copper-blue ZnS luminescence, suggesting that the activator ions are physically located in regions of high oxygen concentration. Silver-blue luminescence is generally assumed to be a transition between a shallow donor (e.g., Cl_S⁻ or Al_{Zn}⁺) and a substitutional silver ion in a zinc site (Ag_{Zn}⁺) [32,41]. However, silver-activated ZnS phosphor and scintillator are usually grown using chlorine fluxes [2] which, in addition to providing charge compensating donor levels, also function to distribute oxygen evenly in the crystal and enhance luminescence

4.2 Application to data from scintillating samples

The emission [16] and absorption/excitation- [38] band diagrams of ZnS with oxygen impurity have recently been revised and presented. These band diagrams assume a splitting of the conduction band due to the isoelectronic oxygen, resulting in a level below the pure conduction band of ZnS (known as E). Exact positions of the defect levels depend on the dissolved oxygen concentration. In sample F, both 340 nm and 360 nm pumping resulted in blue emission. However, in sample P, there was no luminescence when pumped at 360 nm but primarily green emission when pumped at 340 nm. This result can be interpreted as follows.

Pumping from the bottom of the SA(I) impurity level to the E band (lower split of conduction band due to oxygen), is calculated at 342 nm (at 80 K) [38], which is very close to the experimentally observed 340 nm PLE maximum in the scintillating samples. Pumping from the bottom of the Cu(I) defect is E is calculated at 349 nm (for 1 mol% O in ZnS) or 357 nm (for 2 mol% O in ZnS). Emission, then, can be described as from the E. band to the excited level of the SA(I) band, resulting in 445 nm (blue) emission, while emission from an interstitial copper (or similar, such as silver) to the top of the Cu(I) band is 505 nm (green) [16]. Thus the excitation-emission pairs for the defects can be summarized as 342 nm (ex)/445 nm (em) for SA(I)↔E, 349-357 nm (ex)/450 nm (em) for Cu(I)↔E, and 381 nm (ex)/505 nm (em) for Cu_i↔Cu(I) donor-acceptor pair emission, with the energy difference being the Stokes shift. Thus 360 nm pumping can definitely populate the Cu_i (or similar) localized defect from the Cu(I) ground state, and may be able to populate the E. band, if the local oxygen content is high (~2 mol% O). On the other hand, the 340 nm pumping can populate Cu_i and the E band from SA(I) and Cu(I) and probably other analogous defects such as Ag(I). Emissions in the blue are due to transitions from the E. band, and those in the green due to transitions from the localized Cu_i level. Sample F thus had some regions with a deeper E., suggesting higher oxygen levels, resulting in pumping of the E. band even with 360 nm. Sample P did not have these lower conduction band levels, presumably due to lower local oxygen concentration, thus 360 nm could only pump Cu_i, resulting in predominantly green emission (with some very weak blue).

Oxygen content in several samples of single-crystal and polycrystalline ZnS, similar to the ones tested here, has been determined to be ~0.1 mol% by a gas analysis method [35]. The fact that some of these are scintillating and some are not supports the idea that the position of the oxygen in the lattice and its local concentration are responsible for the luminescence and scintillation. The energy bands for 0.1 mol% oxygen show no levels that can be pumped at 340 nm [38], and even if they could, emissions are only in the ultraviolet range [16]. This does not match the data reported here, suggesting that a measure of the overall oxygen concentration does not represent the *local* conditions responsible for luminescence and scintillation. In this respect, HIP has been shown to cause a redistribution of oxygen, presumably from non-optically active twin and grain boundaries to emitting lattice sites [37]. It is likely that this

distribution of oxygen is inhomogeneous and affected by local transition metal defects for reasons of lattice strain compensation, resulting in locally high concentrations of oxygen and smaller local bandgaps, as has been described previously.

ZnS samples tested which showed strong scintillation also showed clear PL, and those that did not scintillate showed poor PL. The role of oxygen in ZnS luminescence and scintillation should thus be carefully considered. Similarly, work on cerium-doping in ZnS suggested that it was the oxygen impurity from CeF_3 additions that led to increased light output [42]. Recently there has been renewed interest in rare-earth doping of ZnS nanoparticles [43], and studies showing enhanced light output with nanoparticles may in fact be due to surface states involving oxygen [44] in combination with rare earth or traditional transition metal (silver, copper) dopants in ZnS [39].

A somewhat similar two-peak scintillation emission is reported for Ti^{3+} doped Al_2O_3 [45]. This behavior is attributed to the interaction of the Ti^{3+} emission with intrinsic defects that are known to be optically active in pure alumina. By contrast, the non-scintillating samples of ZnS examined here exhibited no luminescence under UV stimulation. Exciton formation in ZnS requires very short wavelength (at least hard UV) intense illumination [17], and scintillation mechanisms in wide bandgap semiconductors like ZnS are likely to be different than insulators like Al_2O_3 . Further measurements on samples of known intrinsic defect density will be required to fully elucidate the details of the scintillation observed in ZnS.

5 Summary and Conclusions

Alpha particle scintillation has been observed in visibly transparent single and polycrystalline bulk ceramic ZnS samples 1 - 7 mm thick. Scintillation events were recorded in time using a fast CCD camera, and the best samples showed discrete interaction events between the α -particle with the scintillator, which could be located in space and time and which travelled through the thickness of the scintillator to reach the detector. ZnS scintillators, most made by chemical vapor deposition (CVD), show comparable brightness to commercial ZnS:Ag scintillator screens, which are opaque beyond a few hundred micrometers. The pulse-height spectrum of the CVD sample shows peaks in two channels, believed to be due to the two colors (blue and green) of emission light present when these samples are excited by photoluminescence (PL) at 340 nm, but other interpretations are possible. Samples showed inhomogeneous scintillation that appeared spatially correlated with fluorescence. Based on the PL and PLE results, the origin of the scintillating defects in CVD ZnS are assigned to defect complexes related to isoelectronic oxygen as well as low concentrations of copper impurities. The discovery of scintillation in bulk transparent ZnS suggests possible applications where thick transparent scintillators are desired.

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7 References

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Figures

Figure 1: iQID experimental imaging setup for testing the scintillation response in ZnS using an alpha emitter.

Figure 2: iQID images for (a) Eljen Phosphor EJ-440, where it is placed on top of CVD ZnS (sample F) and light transmitted through 0.25 mm polyester backing plus 4.71 mm CVD ZnS; this gives a comparable optical response to (b) CVD ZnS sample F; (c) photograph of CVD ZnS (sample F) showing the good transparency of the sample through its ~5 mm thickness. The overall size of the sample can also be seen from the contrast in (b).

Figure 3: iQID camera images of scintillating ZnS samples: (a) single crystal sample M, 1 x 1 x 0.1 cm; (b) CVD sample P; (c,d) CVD sample V; scintillation from alpha particles (c), fluorescence from ultraviolet excitation (d); contrast at the edge of the samples shows the transmission of some scintillation light out the sides of the samples; (e) photograph of sample F under ultraviolet light showing the presence of fluorescing defects.

Figure 4: Pulse-height spectrum comparing CVD ZnS (sample F) and commercial ZnS powder scintillator screen (EJ-440).

Figure 5: PLE (a) and PL (b) spectra for sample F.

Figure 6: PLE (a) and PL (b) spectra for sample P.

Figure 7: PLE (a) and PL (b) spectra for sample V.

Figure 8: PLE (a) and PL (b) spectra for the ZnS screen (sample S, EJ-426).

Figure 9: PLE (a) for green emission, note S intensity is right scale, and PL (b) comparison for the ZnS samples

455 Table 1: Qualitative summary of scintillating ZnS materials, indicating whether both sides (front/back) or
 456 only one was scintillating.

Sample	Origin	Scintillating sides	Alpha Response
F	Custom processed IR Window (CVD-HIP)	One	Bright with some very bright regions
V	Commercial IR window (CVD-HIP)	One	Some very bright regions
P	Commercial IR Window (CVD-HIP)	One	Bright
M	Commercial single crystal (Bridgman)	Both	Bright
S	Commercial $^6\text{LiF}/\text{ZnS}:\text{Ag}$ powder screen (EJ-426)	Both	Very bright
N	Commercial $\text{ZnS}:\text{Ag}$ powder screen (EJ-440)	Both	Very bright