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# X-RAY FLUORESCENCE MEASUREMENTS OF 412 INORGANIC COMPOUNDS*

S. E. Derenzo, W. W. Moses, and J. L. Cahoon
Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720

T. A. DeVol
Department of Nuclear Engineering,The University of Michigan, Ann Arbor, MI 48109

L. Boatner
Oak Ridge National Laboratory, Oak Ridge, TN 37830

## ABSTRACT

In a search for new, fast, inorganic scintillators, we have exposed 412 inorganic compounds to 0.5 ns pulses of 20 keV x-rays and measured their fluorescent emissions. Most of these compounds were dense (>4 g/cm$^3$), contained heavy cations such as Pb, Bi, Ba, or a rare-earth element, and anions such as O, F, Cl, Br, I, $CO_3$, $SO_4$, and $PO_4$. About half were undoped compounds and half contained 0.1% to 10% rare-earth dopants. Standard scintillators such as $BaF_2$ and BGO were included for reference. In this Conference Record we report total luminosities and fitted exponential decay times and percentages for 97 compounds having either a luminosity > 40% of BGO, or an initial photon intensity greater than BGO, or a component decay time <1 ns. Emission wavelengths are listed for 53 of these compounds. Significant fast emissions were seen from $Y_2SiO_5$(Ce), $CeCl_3$, $BaCl_2$, $PbSO_4$, and $LuPO_4$(Ce). Other less luminous compounds $Yb_2O_3$, CuI, CuBr, and $BiPO_4$(Gd) exhibited components with shorter decay times than ZnO(Ga) and $BaF_2$.

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## 1 BACKGROUND

The background, motivation, and method for this search has been previously reported [1] (Figure 1). In summary, we seek scintillators able to detect energetic (> 400 keV) gamma rays with good full-energy detection efficiency, timing resolution, and light output. Our method exposes compounds in powdered form to pulses of synchrotron x-rays, permitting the testing of many more compounds than is possible using the traditional method of using gamma-ray sources and optical-quality crystals. The costly and time-consuming step of growing crystals can then be limited to the small fraction of compounds that appear promising in powdered form. Because this method is primarily sensitive to fluorescence from the surface of the powder, it can lead to "false positives," as some compounds absorb their own fluorescent emissions (radiation trapping) and therefore do not scintillate. Only after a crystal sample is shown to have fluorescent emissions whose intensity depends on the amount of ionizing energy deposited in the bulk of the crystal (e.g. a gamma-ray photopeak), is the compound established as a scintillator.

In previous work [1], we reported on the x-ray fluorescence properties of 85 compounds. In this work we expanded the number of samples to 412 and provide data on 97 of these compounds in this Conference Record.

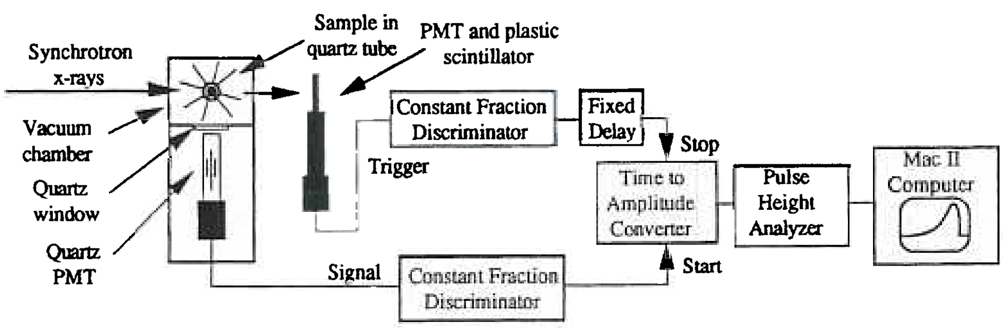


Figure 1. Experimental method for using synchrotron x-rays to measure the fluorescence decay timing spectrum of compounds in powdered form.

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## 2 METHOD

In this work, 412 compounds were exposed to 0.5 ns pulses of 20 keV monochromatic x-rays at the Brookhaven National Laboratory National Synchrotron Light Source (NSLS). Approximately 0.2 ml of each powder was placed in a cylindrical suprasil fused silica vial 5 mm in diameter with 0.37 mm wall thickness, and the tube was sealed with a plastic cap. A 20 keV x-ray beam is not significantly attenuated by the wall of the tube (attenuation length 1.2 mm). A Hamamatsu R2059 phototube with a fused silica window was used to detect any fluorescent emissions (Figure 1). Single photoelectrons were counted, and a pinhole was placed in front of the phototube for the more luminous compounds to reduce the detection rate to a small fraction of the 1.8 MHz x-ray excitation rate. The x-ray beam was aimed so that a portion missed the edge of the tube and was detected by a plastic scintillator and phototube detector which provided a trigger pulse [2] for the oscilloscope and the fluorescent decay time measurements described in the next section.

## 3 RESULTS

### *3.1 Fluorescent Luminosity*

As described in reference [1], the total fluorescent luminosity was determined from the single photoelectron rate by correcting for counter deadtime, subtracting phototube background, adjusting for the synchrotron beam current, correcting for optical depth, and normalizing to a value of 1000 for BGO. Uncertainties in optical depth of the powdered samples prevented us from estimating the luminosity with an accuracy better than a factor of 3. We did not correct for the wavelength-dependent quantum efficiency of the phototube.

All purity data listed in Table 1 was provided by the manufacturers. In some cases the impurities could have significantly effected the observed emissions, either by acting as fluorescent emitters or by acting to quench the fluorescence.

### *3.2 Fluorescent Decay Times and Percentages*

The fluorescence decay timing spectrum decay time was measured using the delayed coincidence method [3]. A single photoelectron pulse was used to start a time-to-amplitude converter (TAC). A delayed trigger pulse from the plastic scintillator stopped the TAC. A sum of up to three exponential decay components were fit to the time delay distribution as needed to achieve an acceptable chi squared (usually <1000 with 760 degrees of freedom). A constant background was added to make the total number of photons in the fit equal to the number measured. Since the beam repetition period was 560 ns, fitting to components with a decay time longer than 10 μs was usually not possible.

The best fit values for decay times and percentages were determined by varying all parameters to achieve a minimum $\chi^2 = K$. Statistical uncertainties in the decay times and percentages were determined by finding the largest and smallest value of each parameter that gave a minimum $\chi^2$ equal to $K + 1$ when that parameter was held fixed and all other parameters were varied. Typical uncertainties in fitted decay times ranged from 2% of the decay time for luminous components to over 20% of the decay time for weak components. Uncertainties in component intensities ranged from 0.1% to over 50%.

Table 1 lists luminosities, exponential decay times, and fractions for 97 compounds having either a luminosity > 40% of BGO, or an initial intensity >BGO, or a component decay time <1 ns. For doped compounds, percentages of dopants are by weight. For a list of all 150 compounds with an observed luminosity > 0.5% of BGO, their luminosity, fitted exponential decay times, percentages, and uncertainties, and a list of the remaining 260 compounds of lower luminosity, see reference [4].

### *3.3 Fluorescent Wavelengths*

The emission spectra of 52 compounds were measured by placing a 0.125 meter Jarrell-Ash MonoSpec Monochromator between the sample and the quartz phototube (Table 2). The single photoelectron rate was recorded as the monochromator wavelength was scanned by computer control for two gratings, one blazed for 300 and the other blazed for 500 nm. The data were not corrected for the wavelength-dependent responses of either the monochromator or the phototube. For a more complete list of wavelengths, see reference [4].

## 4 CONCLUSIONS

Compounds with high atomic number and promising luminosity and speed include $PbSO_4$ (see reference [5]), $CeCl_3$ (brighter than BGO with 70% 23 ns), $BaCl_2$ (brighter than BGO with 36% 1.2 ns). Other less luminous compounds (such as CuI, $Yb_2O_3$, CuBr, and $BiPO_4$(Gd)) exhibited fluorescence components faster than ZnO(Ga) and $BaF_2$ (<0.5 ns). These compounds are interesting enough to prepare in single crystal form for further study.

## 5 ACKNOWLEDGEMENTS

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Table 1 Luminosity and fitted decay components of 97 compounds excited by 20 keV synchrotron x-radiation[a]

| Formula | L[a] | Purity (%) | Color of powder | ρ (g/cc) | Exponential decay time (percentages) |
|---|---|---|---|---|---|
| $Y_2SiO_5$ + Ce[b,c] | 17354 | | clear[d] | 2.70 | 19.7 ns (32.4%), 50 ns (66.3%), >10 µs (1.3%) |
| $SnPO_3F$ | 8523 | | white | 3.50 | 693 ns (14.6%), >10 µs (85.4%) |
| $SrF_2$[c] | 4473 | | white | 4.24 | 19.9 ns (2.0%), 408 ns (63.3%), >10 µs (34.8%) |
| Pilot U (plastic) | 4056 | | white | 1.03 | 1.5 ns (73.3%), 9.3 ns (11.0%), 97 ns (6.5%), >10 µs (9.2%) |
| $CeCl_3$[c] | 3469 | 99.9 | white | 3.90 | 4.4 ns (6.6%), 23.2 ns (69.6%), 70 ns (7.5%), >10 µs (16.3%) |
| $BaF_2$[c] | 3171 | | white | 4.83 | 0.7 ns (5.3%), 66 ns (6.4%), 444 ns (82.9%), >10 µs (5.5%) |
| $BaCl_2$[c] | 3002 | tech | white | 3.90 | 1.2 ns (36%), 3.5 ns (1.1%), 58 ns (24.5%), >10 µs (38.4%) |
| NE102 (plastic) | 2555 | | white | 1.03 | 1.9 ns (69%), 10.4 ns (11.9%), 108 ns (5.7%), >10 µs (13.4%) |
| $ScPO_4$ + 1% $Tb_2O_3$ | 2293 | 99.99 | lt. yellow[d] | 3.71 | >10 µs (100%) |
| $ThCl_4$[c] | 2142 | 99.9 | lt. gray | 4.59 | 24.5 ns (1.2%), 1.7 µs (76.6%), >10 µs (22.2%) |
| $SrCl_2$ + 0.3% Eu | 2126 | 99.99 | clear[d] | 3.05 | 1.6 µs (100%) |
| $ScPO_4$ + 5% $Eu_2O_3$[c] | 2080 | 99.99 | clear[d] | 3.71 | 2.7 ns (0.4%), 30 ns (2.3%), 380 ns (47%), >10 µs (50.3%) |
| $SrI_2$ | 1986 | 95 | white | 4.55 | 8.6 ns (1.5%), 53 ns (6.1%), 394 ns (92.5%) |
| $ScPO_4$ + 3% $^{161}Dy_2O_3$ | 1850 | 99.99 | lt. pink[d] | 3.71 | 5.9 ns (0.6%), >10 µs (99.4%) |
| SrO | 1842 | 99.95 | white | 4.70 | 2.3 ns (0.9%), 80 ns (1.7%), >10 µs (97.4%) |
| $ScPO_4$ + 2% $^{163}Dy_2O_3$ | 1761 | 99.99 | clear[d] | 3.71 | 3.7ns (0.4%), 30.8 ns (2.4%), 339 ns (43.6%), >10 µs (53.7%) |
| $ZrO_2$ | 1482 | 99+ | white | 5.60 | 1.01 µs (33.2%), >10 µs (66.8%) |
| $CaWO_4$ | 1325 | | white | 6.06 | 20 ns (0.4%), 3.6 µs (99.6%) |
| $YPO_4$ + 1% Tb[c] | 1209 | 99.99 | clear[d] | 4.31 | >10 µs (100%) |
| $YPO_4$ + 0.6% $^{161}Dy_2O_3$[c] | 1122 | 99.99 | lt. yellow[d] | 4.31 | >10 µs (100%) |
| $CaMoO_4$ | 1036 | 99.9+ | white | 4.40 | 8.4 µs (100%) |
| $ScPO_4$ + 2% $Yb_2O_3$[c] | 1024 | 99.99 | clear[d] | 3.71 | 21.1 ns (81.9%), 122 ns (2.3%), >10 µs (15.1%) |
| $Bi_4Ge_3O_{12}$ (BGO)[c] | 1000 | 99.99995 | white | 7.13 | 4.6 ns (1.1%), 45.5 ns (7.8%), 277 ns (90.3%) |
| $ScPO_4$ + 10% $Sm_2O_3$[c] | 993 | 99.99 | lt. yellow[d] | 3.71 | 6.3 ns (2.0%), 36.3 ns (8.7%), >10 µs (89.3%) |
| $YPO_4$ + 9% $^{163}Dy_2O_3$ | 983 | 99.99 | lt. yellow[d] | 4.31 | >10 µs (100%) |
| $YPO_4$ + 1% $Dy_2O_3$[c] | 963 | 99.99 | lt. yellow[d] | 4.31 | >10 µs (100%) |
| $YPO_4$ + 0.7% $^{162}Dy_2O_3$ | 884 | 99.99 | lt. yellow[d] | 4.31 | >10 µs (100%) |
| $ZnWO_4$ | 869 | 98 | white | 7.87 | 936 ns (11.3%), >10 µs (88.7%) |
| $SrCl_2$ + 0.2% Lu[c] | 862 | 99.99 | clear[d] | 3.05 | 9.2 ns (0.3%), 485 ns (87.7%), >10 µs (12.1%) |
| $LuPO_4$ + 0.6% $^{161}DyO_3$ | 820 | 99.99 | clear[d] | 6.53 | 13.6 ns (0.2%), >10 µs (99.8%) |
| $YPO_4$ + 2% $Tm_2O_3$ | 815 | 99.99 | lt. yellow[d] | 4.31 | >10 µs (100%) |
| $ScPO_4$ + 3% $Sm_2O_3$ | 797 | 99.99 | clear[d] | 3.71 | 1.2 ns (0.2%), 26.2 ns (5.8%), 75 ns (14.4%), >10 µs (79.5%) |
| $SrCl_2$ + 0.2% Co | 777 | 99.99 | clear[d] | 3.05 | 3.7 ns (0.2%), 496 ns (94.0%), >10 µs (5.8%) |
| $ScPO_4$ + 2% $Nd_2O_3$[c] | 724 | 99.99 | clear[d] | 3.71 | 3.4 ns (0.3%), 62 ns (11.2%), 404 ns (35.2%), >10 µs (53.3%) |
| $LuPO_4$ + 1% Ce[c] | 591 | 99.99 | clear[d] | 6.53 | 5.1 ns (4.0%), 23 ns (87.6%), >10 µs (8.4%) |
| $ScPO_4$ + 2% $^{145}Nd_2O_3$[c] | 578 | 99.99 | clear[d] | 3.71 | 3.8 ns (0.4%), 48.7 ns (10.0%), 152 ns (36.3%), >10 µs (53.4%) |
| $MgWO_4$ | 571 | 99 | white | 5.66 | >2 µs (100%) |
| $LuPO_4$ + 0.6% $^{163}Dy_2O_3$ | 547 | 99.99 | clear[d] | 6.53 | >8 µs (100%) |
| $LuCl_3$[c] | 541 | 99.9 | white | 3.98 | 4.5 ns (2.1%), 28.5 ns (3.9%), 254 ns (25.2%), >10 µs (68.7%) |
| $PbSO_4$[c] | 517 | 99.999 | white | 6.20 | 7.4 ns (7.2%), 33.7 ns (21.3%), 168 ns (45.9%), >10 µs (25.7%) |
| $TlPF_6$[c] | 496 | | white | 4.63 | <0.6 ns (0.4%), 26 ns (2.7%), 399 ns (74.4%), >10 µs (22.5%) |
| $LuPO_4$ + 0.25% $Dy_2O_3$ | 474 | 99.99 | clear[d] | 6.53 | >10 µs (100%) |
| $CeF_3$ | 436 | | white | 6.16 | 4.2 ns (31.8%), 23.6 ns (55.8%), >10 µs (12.4%) |
| $ScPO_4$ + 0.7% $VO_2$[c] | 431 | 99.99 | clear[d] | 3.71 | 3.6 ns (0.9%), 26.2 ns (5.0%), 103 ns (61.3%), >10 µs (32.9%) |
| $ScPO_4$ + 2% NiO[c] | 413 | 99.99 | clear[d] | 3.71 | 5.9 ns (1.6%), 36.8 ns (7.1%), 98 ns (59.4%), >10 µs (31.9%) |
| $La_2(ZrO_3)_3$ | 404 | | white | 5.00 | 2.6 ns (0.4%), 94 ns (3.3%), >10 µs (96.3%) |
| ZnO + Ga[c] | 396 | | lt. gray | 5.61 | 0.6 ns (97.5%), >10 µs (2.5%) |
| $YPO_4$ + 5% $Nd_2O_3$[c] | 364 | 99.99 | lt. yellow[d] | 4.31 | 10.3 ns (15.4%), 27 ns (30.3%), 142 ns (24.9%), >10 µs (29.4%) |

[a] Luminosity in the 160- 580 nm wavelength range, corrected for optical depth, and normalized to BGO = 1000.

[b] P47 phosphor

[c] Wavelengths given in Table 2

[d] small crystals

Table 1 (continued) Luminosity and fitted decay components of 97 compounds excited by 20 keV synchrotron x-radiation[a]

| Formula | L[a] | Purity (%) | Color of powder | ρ (g/cc) | Exponential decay times (percentages) |
|---|---|---|---|---|---|
| $Y_2O_3$[c] | 354 | | white | 5.00 | 4.9 ns (6.8%), 22.5 ns (26.9%), 62 ns (62.8%), >10 µs (3.6%) |
| $LuF_3$[c] | 346 | | white | 8.32 | 0.8 ns (1.0%), 43.9 ns (2.3%), >10 µs (96.7%) |
| $YF_3$[c] | 285 | 99.9 | white | 4.01 | 0.7 ns (1.5%), 21.3 ns (1.4%), 576 ns (16.9%), >10 µs (80.2%) |
| $ZnO$[c] | 253 | | clear[d] | 5.61 | 0.5 ns (0.7%), 1.48 µs (57.6%), >10 µs (41.7%) |
| $Ga_2O_3$ | 251 | 99.999 | white | 5.88 | 1.6 ns (8.0%), 14.5 ns (14.5%), 112 ns (22.0%), >10 µs (55.6%) |
| $RbCaF_3$[c] | 226 | 99.99 | clear[d] | 3.43 | 1.3 ns (21.8%), 2.8 ns (31.3%), 13.1 ns (1.6%), >10 µs (45.4%) |
| $Tb_2(SO_4)_3$ | 203 | 99.9 | white | 5.00 | <0.5 ns (0.2%), >10 µs (99.8%) |
| $TbF_3$[c] | 200 | 99.9 | white | 7.23 | 0.7 ns (0.3%), >10 µs (99.7%) |
| $YPO_4$ + 2% $Pr_2O_3$[c] | 191 | 99.99 | lt. yellow[d] | 4.31 | 8.7 ns (24.3%), 20.5 ns (14.9%), >10 µs (60.8%) |
| $BaHPO_4$[c] | 183 | | white | 4.10 | 0.6 ns (5.7%), 75 ns (11.6%), 545 ns (82.7%) |
| $AgBF_4$[c] | 160 | 99 | off-white | 4.37 | <0.5 ns (1.4%), 126 ns (6.3%), >10 µs (92.3%) |
| $SnSO_4$ | 152 | 95+ | white | 4.28 | <0.5 ns (0.6%), 25.4 ns (0.9%), >10 µs (98.5%) |
| $ZnO$[c] | 133 | 99.9+ | white | 5.67 | <0.5 ns (4.8%), 8 ns (1.8%), 224 ns (14.6%), >10 µs (78.8%) |
| $CdI_2$[c] | 106 | 99 | white | 5.67 | 1.4 ns (45.6%), 6 ns (29.9%), 45.2 ns (14.2%), >10 µs (10.3%) |
| $Eu_2O_3$ | 99 | | pale rose | 7.42 | <0.5 ns (0.3%), >10 µs (99.7%) |
| $Rb_2CO_3$[c] | 96 | 99.9 | white | 3.40 | <0.5 ns (2.2%), >10 µs (97.8%) |
| $CuI$[c] | 73 | 98 | off-white | 5.62 | <0.5 ns (88%), >10 µs (12%) |
| $ZrSiO_4$ | 72 | 98 | white | 4.56 | <0.6 ns (0.7%), 14.6 ns (2.7%), 140 ns (23.5%), >10 µs (73.1%) |
| $EuF_3$[c] | 72 | 99+ | white | 6.50 | 0.6 ns (0.7%), >10 µs (99.3%) |
| $2(PbCO_3)_2 \cdot Pb(OH)_2$[c] | 64 | 99.999 | white | 6.14 | 4.3 ns (24.5%), 16.9 ns (37.1%), 73 ns (29.6%), >10 µs (8.7%) |
| $CdBr_2$ | 63 | 99 | white | 5.19 | <0.5 ns (6.8%), 5.7 ns (11.8%), 24 ns (12.9%), >10 µs (68.5% |
| $PbWO_4$[c] | 60 | 99.998 | white | 8.23 | 1.6 ns (27%), 9.3 ns (35.9%), 37 ns (22.8%), >10 µs (14.3%) |
| $RbMgF_3$[c] | 55 | 99.99 | clear[d] | 4.30 | <0.5 ns (1.2%), 13.1 ns (0.4%), >10 µs (98.3%) |
| $AgNO_2$ | 48 | 99 | white | 4.45 | <1 ns (1.0%), >10 µs (97.7%) |
| $TaF_5$ | 40 | 99 | off-white | 4.74 | <0.8 ns (1.2%), 19.3 ns (3.7%), 134 ns (13%), >10 µs (82.1%) |
| $PbCO_3$[c] | 38 | 99.999 | white | 6.60 | 2.9 ns (30.9%), 15.1 ns (37.3%), 80 ns (17.9%), >10 µs (13.9%) |
| $ZnMoO_4$ | 35 | 98+ | off-white | 5.63 | 0.9 ns (0.7%), >10 µs (99.3%) |
| $CdCl_2$ | 34 | 99+ | white | 4.00 | <0.5 ns (3.3%), 21.3 ns (22.3%), 1.09 µs (74.5%) |
| $PbF_2$ + 0.5% Tb[c] | 31 | | white | 8.24 | <0.5 ns (1.1%), >10 µs (98.9%) |
| $PbCl_2$[c] | 31 | | white | 5.90 | 2.0 ns (35%), 19.5 ns (19.4%), >10 µs (45.6%) |
| $BaBr_2$[c] | 30 | | white | 4.78 | <0.5 ns (2.9%), 28.5 ns (0.8%), >10 µs (96.3%) |
| $Lu_2O_3$ | 28 | 99.9 | white | 9.42 | 0.8 ns (9.5%), 25.2 ns (4.8%), 302 ns (30.7%), >10 µs (55% |
| $3(Zn(OH)_2) \cdot 2(ZnCO_3)$ | 24 | | white | 4.40 | 0.6 ns (3.7%), >10 µs (96.3%) |
| $SrZrO_3$ | 24 | 95 | white | 5.46 | 0.8 ns (0.7%), 17.6 ns (6.9%), 183 ns (20.5%), >10 µs (71.9%) |
| $ZnF_2$[c] | 24 | | white | 4.95 | 0.9 ns (7.2%), 10.3 ns (10.6%), 86 ns (15.3%), >10 µs (66.9%) |
| $PbF_2$ + 2% $TbF_3$ | 20 | | white | 8.24 | 0.5 ns (1.6%), >10 µs (98.4%) |
| $Dy_2(SO_4)_3$ | 19 | 99.9 | white | 3.75 | <0.5 ns (2.0%), 473 ns (23%), >10 µs (75%) |
| $Eu_2(WO_4)_3$[c] | 15 | | white | 7.37 | <0.5 ns (0.9%), 77 ns (3.3%), >10 µs (95.8%) |
| $Tb_2(CO_3)_3 \cdot X(H_2O)$[c] | 14 | 99.9 | white | 6[e] | <0.6 ns (1.6%), 42.2 ns (1.0%), >10 µs (97.4%) |
| $Yb_2O_3$[c] | 13 | 99.9 | white | 9.17 | <0.5 ns (72.7%), >10 µs (27.3%) |
| $YPO_4$ | 13 | 99.9 | white | 4.30 | <0.6 ns (2.4%), 282 ns (7.4%), >10 µs (90.2%) |
| $La_2(WO_4)_3$ | 13 | | lt. green | 6.63 | <0.5 ns (1.3%), 279 ns (72.1%), >10 µs (26.6%) |
| $TlCl$ | 12 | 99.999 | white | 7.00 | 0.6 ns (25.9%), 3.4 ns (37.7%), 11.2 ns (18.2%), >10 µs (18.2%) |
| $CuBr$ | 11 | 99 | off-white | 5.00 | <0.6 ns (43.4%), 6.4 ns (18.7%), >10 µs (37.9%) |
| $ErF_3$[c] | 8 | 99.99 | lt. pink | 7.81 | 0.6 ns (4.3%), 42 ns (17.3%), >10 µs (78.4%) |
| $PbBr_2$ | 6 | 99.999 | white | 6.66 | 0.9 ns (13.6%), 8.3 ns (20.2%), 69 ns (23.2%), >10 µs (43%) |
| $Pb_2P_2O_7$[c] | 4 | 99.99 | clear[d] | 5.80 | 1.1 ns (17.4%), 7 ns (20.1%), 75 ns (23.5%), >10 µs (39.0%) |
| $BiPO_4$ + 1% Gd[c] | 2 | | white | 6.32 | <0.6 ns (21.4%), 3.3 ns (15.6%), 20.4 ns (8.5%), >10 µs (54.5%) |

[a] Luminosity in the 160- 580 nm wavelength range, corrected for optical depth, and normalized to BGO = 1000.
[c] Wavelengths given in Table 2
[d] small crystals
[e] Density unavailable- value shown was assigned solely to permit calculation of luminosity

Table 2 Fluorescence Emission Wavelengths[a]

| Formula | Wavelengths (nm) | Formula | Wavelengths (nm) |
|---|---|---|---|
| $AgBF_4$ | | $ScPO_4$ + 2% $^{145}Nd_2O_3$ | 220, 290, 320, 360, 390, 480, |
| $BaBr_2$ | | | 540 |
| $BaCl_2$ | | $ScPO_4$ + 2% $Nd_2O_3$ | 220, 290, 320, 360, 390, 480, |
| $BaF_2$ | | | 540 |
| $BaHPO_4$ | | $ScPO_4$ + 2% NiO | 220, 310, 380, 480 |
| $Bi_4Ge_3O_{12}$ (BGO) | | $ScPO_4$ + 2% $Yb_2O_3$ | 280, 370 |
| $BiPO_4$ + 1% Gd | | $ScPO_4$ + 5% $Eu_2O_3$ | 360, 620 |
| $CdI_2$ | | $ScPO_4$ + 10% $Sm_2O_3$ | 210, 310, 570 |
| $CeCl_3$ | | $SrCl_2$ + 0.2% Lu | 370 |
| CuI | | $SrF_2$ | 300 |
| $ErF_3$ | | $SrI_2$ | 510 |
| $Eu_2(WO_4)_3$ | | $Tb_2(CO_3)_3 \cdot X(H_2O)$ | 490, 550 |
| $EuF_3$ | | $TbF_3$ | 490, 550 |
| $LuCl_3$ | | $ThCl_4$ | 340 |
| $LuF_3$ | | $TlPF_6$ | 210, 320, 370 |
| $LuPO_4$ + 1% Ce | | $Y_2O_3$ | 340 |
| $2(PbCO_3)_2 \cdot Pb(OH)_2$ | | $Y_2SiO_5$ + Ce | 440 |
| $Pb_2P_2O_7$ | | $Yb_2O_3$ | 350 |
| $PbCl_2$ | | $YF_3$ | 310, 380, 410, 480, 570 |
| $PbCO_3$ | | $YPO_4$ + 0.6% $^{161}Dy_2O_3$ | 360, 480, 580 |
| $PbF_2$ + 0.5% Tb | | $YPO_4$ + 1% $Dy_2O_3$ | 240, 480, 580 |
| $PbSO_4$ | | $YPO_4$ + 1% Tb | 380, 410, 490, 550, 590 |
| $PbWO_4$ | | $YPO_4$ + 2% $Pr_2O_3$ | 240, 270, 470, 490, 600 |
| $Rb_2CO_3$ | | $YPO_4$ + 5% $Nd_2O_3$ | 190, 240, 280 |
| $RbCaF_3$ | | $ZnF_2$ | 340 |
| $RbMgF_3$ | | ZnO + Ga | 390 |
| $ScPO_4$ + 0.7% $VO_2$ | | ZnO | 390, 510 |

[a] Wavelength data near 430 nm contaminated by a light leak

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