Title
Experimental Efforts and Results in Finding New Heavy Scintillators

Authors
Derenzo, S.E.
Moses, W.W.

Publication Date
1992-09-22

LBL-33295
UC-407

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Presented at the CRYSTAL 2000 International Workshop on Heavy Scintillators for Scientific and Industrial Applications, Chamonix, France, September 22–26, 1992, and to be published in the Proceedings

Experimental Efforts and Results in Finding New Heavy Scintillators

S.E. Derenzo and W.W. Moses

September 1992

Donner Laboratory

Biology & Medicine Division

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

DISCLAIMER

LBL-33295
UC-407

Experimental Efforts and Results in Finding New Heavy Scintillators

Stephen E. Derenzo and William W. Moses

Life Sciences Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

September 1992

This work was supported by the National Institutes of Health under Grant R01-CA48002, by a grant from the Whitaker Foundation, and by the Director, Office of Energy Research, Office of Health and Environmental Research, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

EXPERIMENTAL EFFORTS AND RESULTS IN FINDING NEW HEAVY SCINTILLATORS*

Stephen E. Derenzo and William W. Moses,
Lawrence Berkeley Laboratory, Berkeley, California 94720

Abstract

New heavy scintillators are being discovered with increasing frequency. In recent years NaI(Tl) (with its high light output and energy resolution) has been joined by BGO (with its high stopping power), BaF_2 (with its excellent timing resolution), and CeF_3 (with its speed and short Molière radius). More than 10 potentially useful scintillators have been under development in the past five years, such as $PbSO_4$ and Lu_2SiO_5(Ce). We tabulate the characteristics of these and other scintillators, including wavelength, luminous efficiency, decay time, and initial intensity. We describe a search strategy and the prospects for finding the "ideal" heavy scintillator, which would combine the light output of NaI(Tl) and CsI(Tl), the stopping power of BGO, and the speed of BaF_2 and ZnO(Ga).

* Work supported in part by U.S. DOE contract DE-AC03-76SF00098, in part by U.S. NIH grant R01-CA48002, and in part by a grant from the Whitaker Foundation.

Proceedings of the CRYSTAL 2000 International Workshop on Heavy Scintillators for Scientific and Industrial Applications, Chamonix, France, Sept 22-26, 1992.

1. Introduction

The widespread use of heavy scintillators was initiated in the late 1940's when Robert Hofstadter and co-workers developed NaI(Tl) and demonstrated the use of early photomultiplier tubes to detect scintillation flashes[1-4]. In the 1950's the same research group discovered scintillation in CsF[5] and in pure NaI at 77K[6]. Over the years a number of other useful scintillators have been discovered and developed, and summaries of their properties may be found in references 7-14.

For gamma ray detection and spectroscopy, heavy inorganic scintillators are most often used. In this role, scintillators have a number of desired characteristics:

- The stopping power (the probability of complete absorption of the photon energy), which is enhanced by choosing a high density and high atomic number
- The timing resolution, which is enhanced by a short decay time and a large light output
- The energy resolution, which is enhanced by a large light output
- The dead time, which is reduced by a short decay time
- The wavelength of emission, which should be matched with the spectral response of the photodetector
- Mechanical ruggedness
- Radiation hardness
- Chemical stability in normal atmospheric conditions
- Availability of large, clear crystals at low cost

As summarized in the following section, many scintillators are available, but none excels in all the above properties. As a result, choosing a scintillator requires judicious compromises. In subsequent sections we list both established scintillators, those under development, and candidate compounds that hopefully will be developed to widen the selection of choices.

2. Established Heavy Scintillators

Table 1 lists established heavy scintillators that are either currently or have been in commercial production. Heavy-atom scintillators for gamma-ray detection have been emphasized, but others have been included for reference. For gamma-ray detection, the following are of particular note

- High luminous efficiency (in photons/MeV): NaI(Tl) and CsI(Tl)
- High density, high atomic number, and short gamma-ray attenuation length: BGO
- Short Molière radius: BGO, CeF_3
- High initial photon intensity (in photons/MeV/ns) and an excellent timing resolution: BaF_2
- High luminous efficiency and wavelength suitable for silicon photodiodes: CsI(Tl), $CdWO_4$

Table 1 Properties of Established Heavy Scintillators[a]

	density (gm /cm^3)	μ^{-1} b	hygro- scopic	λ_{max} (nm)	index refr.	photons /MeV	decay time (ns)	photons /MeV /ns	refs
anthracene[c]	1.25	8.79	no	450	1.62	16,000	30	550	11
BaF_2	4.89	2.29	no	195, 220	1.49	1,800	0.8[d]	3,000	13, 15-20
				310		10,000	630	15	
$Bi_4Ge_3O_{12}$	7.13	1.11	no	480	2.15	700	60	12	13, 21-25
				480	2.15	7,500	300	25	
					totals =	8,200	total =	37	
$Bi_4Ge_3O_{12}$(170K)	7.13	1.11	no		2.15	24,000	2,000	12	26
CaF_2(Eu)	3.19	3.72	no	435	1.44	19,000	940	20	4, 8, 13, 27
$CaWO_4$	6.1	1.50	no	430	1.92	6,000	6,000	1	11
$CdWO_4$	7.90	1.21	no	470	2.30	15,000	15,000	1	13, 19, 28
CeF_3	6.16	1.77	no	340	1.62	4,200[e]	27[e]	155[e]	29-35
				300		200[e]	3[e]	65[e]	
CsF	4.11	2.69	very	390	1.48	2,500	2.9[d]	860	5, 13, 36-38
CsI(Na)	4.51	2.43	yes	420	1.84	39,000	630	62	13
CsI(Tl)	4.51	2.43	no	540	1.80	59,000	800[f]	f	13, 28,
						5,400	6,000	1	39, 40
CsI(pure)	4.51	2.43	no	315	1.80	2,300	16	140	13, 41
Gd_2SiO_5(Ce)	6.71	1.50	no	440	1.85	10,000	60	170	13, 42-44
LiI(Eu)	4.08	2.73	very	470	1.96	11,000	1,400	8	13, 45
NaI(Tl)	3.67	3.05	yes	415	1.85	38,000	230	165	13, 28
NaI(77K)[g]	3.67	3.05	yes	303	1.85	76,000	60	1,300	6, 46
NE102A	1.03	10.5	no	425	1.58	10,000	2.4	5,000	11
Pilot U	1.03	10.5	no	425	1.58	10,000	1.36	7,300	11
$ZnWO_4$	7.87	1.19	no	480	2.2	10,000	5,000	2	28

[a] Heavy scintillators emphasized- others included for reference. Data for room temperature unless otherwise noted

[b] Attenuation length (in cm) for 511 keV photons

[c] $C_{14}H_{10}$ (three fused aromatic rings)

[d] cross-luminescence

[e] subject to sample-to-sample variations

[f] 40 ns rise time

[g] Pure (undoped)

3. Heavy Scintillators in Limited Availability

Table 2 lists scintillators that have been studied as single crystals, and whose properties as scintillation detectors have been measured, but are not yet in large-scale commercial production. In the case of $PbCO_3$ and $PbSO_4$, the largest clear crystals available are small samples of natural minerals.

Table 2 Heavy Scintillators in Limited Availability

	density (gm /cm^3)	μ^{-1} a	hygro-scopic	λ_{max} (nm)	index refr.	photons /MeV	decay time (ns)	photons /MeV /ns	refs
$BaLiF_3$			no	240		1,800	<1.0[b]	>1,800	20
$Bi_4Si_3O_{12}$	7.13	1.06	no	480	2.06	1200	100	12	12
CdF_2	6.64	1.76	yes	540	1.55	200	10	20	47
CdS(Te)	4.82	2.39	no	640		190	18	11	48
						3,170	270	12	
						13,640	3,000	5	
						total = 17,000		total = 28	
CsBr(80K)	4.44	2.58	yes	250		1,800	1.34[b]	1,340	38
CsCl	3.99	2.79	yes	245, 270	1.64	900	0.88[b]	1,000	38
$KLuF_4$			no	190		170	1.3[b]	130	20
LaF_3 (Ce)	5.94	1.85	no	290	1.7	220	3.0	73	33, 49
				340		1,890	26.5	71	
						90	185	0.5	
						total = 2,200		total = 145	
LaF_3(Nd)	5.94	1.85	no	173	1.7	1,800	6	300	50
Lu_2SiO_5(Ce)	7.4	1.22	no	420	1.82	30,000	40	750	51, 52
$PbCO_3$	6.6	1.16	no	475	1.80, 2.04	180	2.0	90	53-55
						550	15	37	
						70	92	1	
						total = 800		total = 128	
$PbMoO_4$(100K)	6.92	1.22	no			6,000	11,000	0.5	56
$PbSO_4$	6.4	1.28	no	340	1.85	5,500	5, 26, 135	100	57-59
$PbSO_4$ (170K)	6.4	1.28	no	340	1.85	27,000	300	90	59
						41,000	1,500	27	
						total = 68,000		total = 117	
$YAlO_3$(Ce)	5.35	2.24	no	390	1.94	19,700	31	635	60, 61
$Y_3Al_5O_{12}$(Ce)[c]	4.55	2.63	no	590	1.82	11,000	50, 290		62
Y_2SiO_5(Ce)	2.70	4.43	no	420	1.8	45,000	70	640	63, 64

[a] Attenuation length (in cm) for 511 keV photons

[b] cross-luminescent

[c] also known as YAG

4. Interesting Heavy Compounds not Available as Scintillation-Quality Crystals

For several years we have been using pulsed synchrotron x-radiation to measure the radioluminescence of over 400 compounds in powdered form[65, 66]. The technique is able to make accurate measurements of wavelength and decay times and approximate measurements of luminosity. The decay timing spectrum is measured using the delayed coincidence method of Bollinger and Thomas[67]. Using these methods, we have discovered (or rediscovered) x-ray excited fluorescence from $PbWO_4$, CeF_3, $PbCO_3$, $PbSO_4$, Yb_2O_3, CuI, $BaCl_2$, and $CeCl_3$ in powdered samples (Table 3). Subsequently, we were able to acquire synthetic crystals of $PbWO_4$ and CeF_3, and natural crystals of $PbCO_3$ (cerussite) and $PbSO_4$ (anglesite).

Table 3 X-ray excited fluorescence of heavy compounds not available as crystals

	density (gm /cm^3)	μ^{-1} a	hygro-scopic	λ_{max} (nm)	index refr.	photons /MeV	decay time (ns)	photons /MeV /ns	refs
$BaCl_2$	3.90	2.89	yes	300	1.74	8,600	1.2	7,200	66
				300		5,800	58	100	
						total = 14,400		total = 7,300	
$CeCl_3$	3.90	2.85	yes	360		1,800	4.4	410	66
				360		19,600	23	850	
				360		2,100	70	30	
						4,500		>10 μs	
						total = 28,000		total = 1,290	
CuI	5.62	2.04	yes	430	2.35	600	<0.5	>1,200	66
$LuPO_4$(Ce)	6.53	1.43	no	350		200	5	40	66
				350		4,200	23	180	
						total = 4,400		total = 220	
$PbWO_4$[c]	8.2	0.96	no	460	2.3	140	1.7	82	65, 66
						170	10	17	
						110	38	3	
						70		>10μs	
						total = 490		total = 102	
Yb_2O_3	9.17	0.97	no	350		100	<0.5	>200	65, 66
ZnO(Ga)	5.61	2.16	no	385	2.02	15,000	0.7	21,000	11, 68-70
ZnS(Ag)	4.09	2.94	no	450	2.36	49,000	200	250	10, 11

[a] Attenuation length (in cm) for 511 keV photons

[b] Approximate value- subject to uncertainties in the optical depth of the powders used

[c] Values from measurements of powdered samples[66]. Scintillation measurements of crystal samples in excellent agreement[71]. Recently, large crystals have been grown[72].

Recently, we have described the design of a table-top pulsed x-ray system for this work[73]. It uses a laser diode, a light-excited x-ray tube, and a microchannel phototube. The measured system timing resolution is 109 ps fwhm.

It is interesting to note that in 1947 Robert Hofstadter discovered the high luminosity of NaI(Tl) before growing a crystal. He produced a molten glaze of NaI and Tl halide and placed it on a photographic plate along with samples of anthracene, naphthalene, KI(Tl), NaCl(Tl), KBr(Tl), $CaWO_4$, etc. After exposure to a radium source, the developed film was blackened by the NaI(Tl) powder to a much greater intensity than any of the other samples[1, 2].

5. A Method for Finding New Heavy Scintillators Using the Pulsed X-ray Method

We propose a comprehensive, efficient program for finding new scintillators, which includes the following steps:

1 Identification of promising pure and doped compounds using theoretical or empirical knowledge. Since there are many thousands of dense, heavy atom compounds and each of these could be doped with over 50 elements in a variety of concentrations, some guidance is necessary.

2 Preparation of the compounds identified in step 1 in powdered form. Note that in most cases, the chemical synthesis of a powdered sample is considerably easier than growing a clear crystal ≥ 5 mm in size.

3 Exposing the powdered samples to pulsed x-rays and detecting and measuring interesting (bright, fast, etc.) fluorescent emissions. X-rays provide a broad spectrum of energy transfers and produce thousands of excited neutral and ionized molecules. Photons from a UV lamp are not energetic enough to excite all important scintillator transitions (such as the fast crossover transitions in CsF and BaF_2). A synchrotron VUV beam can provide monoenergetic photons over a wide range of energies, but only crystal samples can be used because an ultra-high vacuum is required.

4 Growing small (≥1 cm^3), clear crystals of the few (<1%) of the compounds found to be interesting in step 3

5 Exposing the crystals from step 4 to gamma rays to detect a photopeak and measure the luminosity, energy resolution and timing resolution. The use of a single crystal sample is necessary to include the effects of self-absorption, which can occur in molecules with non-filled electronic shells. Because this self-absorption can seriously reduce the light output, it is said that "the birth certificate of a new scintillator is its gamma-ray photopeak."

6. Conclusions

1 Theoretical or empirical guidance is vital for a comprehensive and efficient search of new heavy scintillators.

2 There is much work to be done by crystal growers in producing scintillation-quality crystals of compounds with interesting x-ray excited fluorescence emissions.

3 Compared with the tasks of developing a predictive theory and growing large, clear crystals, characterization of powdered and crystal samples is easy.

4 The birth certificate of a new scintillator is its gamma ray photopeak (or monoenergetic charged-particle peak).

5 We may never find the scintillator that is "ideal" for all applications, but the discovery of new scintillators will provide a wider selection of properties for a variety of applications.

7. Acknowledgements

We thank L. Boatner, B. Czirr, A. Lempiki, C. Melcher, P. Schotanus, and M. Weber for helpful discussions. This work was supported in part by the Director, Office of Energy Research, Office of Health and Environmental Research, Medical Applications and Biophysical Research Division of the U.S. Department of Energy under contract No. DE-AC03-76SF000098, in part by Public Health Service Grant R01 CA48002 awarded by the National Cancer Institute, Department of Health and Human Services, and one of us (W.W. Moses) thanks the Whitaker Foundation for support. Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

8. References

1 R. Hofstadter, "Alkali halide scintillation counters," *Phys Rev,* vol. 74, pp. 100-101, 1948.

2 R. Hofstadter, "Twenty five years of scintillation counting," *IEEE Trans Nucl Sci,* vol. NS-22, pp. 13-25, 1975.

3 G. J. Hine, "The inception of photoelectric scintillation detection commemorated after three decades," *J Nucl Med,* vol. 18, pp. 867, 1977.

4 R. L. Heath, R. Hofstadter and E. B. Hughes, "Inorganic scintillators: A review of techniques and applications," *Nucl Instr Meth,* vol. 162, pp. 431-476, 1979.

5 W. V. Sciver and R. Hofstadter, "Gamma- and alpha-produced scintillations in cesium fluoride," *Phys Rev,* vol. 87, pp. 522, 1952.

6 W. J. Van Sciver and L. Bogart, "Fundamental studies of scintillation phenomena in NaI," *IRE Trans Nucl Sci,* vol. NS-5(3), pp. 90-93, 1958.

7 E. Sakai, "Recent measurements on scintillator-photodetector systems," *IEEE Trans Nucl Sci,* vol. NS-34, pp. 418-422, 1987.

8 I. Holl, E. Lorenz and G. Mageras, "A measurement of the light yield of common inorganic scintillators," *IEEE Trans Nucl Sci*, vol. NS-35, pp. 105-109, 1988.

9 G. F. Knoll, "Radiation Detection and Measurement (2nd edition)," pp. 754, John Wiley & Sons, New York, 1989.

10 Bicron Chemical Co. Catalog, Newbury, Ohio

11 Nuclear Enterprises America Catalog, Fairfield, NJ

12 L. V. Viktorov, V. M. Skorikov, V. M. Zhukov, et al., "Inorganic scintillation materials," *Izvestiya Akademii Nauk SSSR, Neorganicheskie Materialy*, vol. 27, pp. 2005-2029, 1991.

13 P. Schotanus, G. Stam, E. Gerritse, et al., "Scintillation detectors," pp. 111, Solon Technologies, Inc., Solon, Ohio, 1992.

14 P. Lecoq and M. Schussler, "Progress and prospects in the development of new scintillators for future high energy physics experiments," *Nucl Instr Meth*, vol. A315, pp. 337-343, 1992.

15 M. R. Farukhi and C. F. Swinehart, "Barium fluoride as a gamma ray and charged particle detector," *IEEE Trans Nucl Sci*, vol. NS-18(1), pp. 200-204, 1971.

16 M. Laval, M. Moszynski, R. Allemand, et al., "Barium fluoride- inorganic scintillator for subnanosecond timing," *Nucl Instr Meth*, vol. 206, pp. 169-176, 1983.

17 W. H. Wong, N. A. Mullani and G. Wardworth, "Characteristics of small barium fluoride (BaF_2) scintillator for high intrinsic resolution time-of-flight positron tomography," *IEEE Trans Nucl Sci*, vol. NS-31, pp. 381-386, 1984.

18 P. Schotanus, C. W. E. Van Eijk, R. W. Hollander, et al., "Photoelectron production in BaF2–TMAE detectors," *Nucl Instr Meth*, vol. A259, pp. 586-588, 1987.

19 C. L. Melcher, R. A. Manente and J. S. Schweitzer, "Applicability of barium fluoride and cadmium tungstate scintillators for well logging," *IEEE Trans Nucl Sci*, vol. NS-36, pp. 1188-1192, 1989.

20 P. Dorenbos, R. Visser, C. W. E. v. Eijk, et al., "Photon yields and decay times of cross luminescence in ionic crystals," *IEEE Trans Nucl Sci*, vol. NS-39, pp. 506-510, 1992.

21 M. J. Weber and R. R. Monchamp, "Luminescence of $Bi_4Ge_3O_{12}$: spectral and decay properties," *J Appl Phys*, vol. 44, pp. 5495-5499, 1973.

22 Z. H. Cho and M. R. Farukhi, "Bismuth germanate as a potential scintillation detector in positron cameras," *J Nucl Med*, vol. 18, pp. 840-844, 1977.

23 M. Moszynski, C. Gresset, J. Vacher, et al., "Timing properties of BGO scintillator," *Nucl Instr Meth*, vol. 188, pp. 403-409, 1981.

24 M. J. Weber, "Discovery of the scintillation properties of BGO: underlying principles," *Proceedings of The International Workshop on Bismuth Germanate*, (Edited by C. N. Holmes), pp 3-20, Princeton University, 1982.

25 S. E. Derenzo, "Gamma-ray spectroscopy using small, cooled bismuth germanate scintillators and silicon photodiodes," *Nucl Instr Meth*, vol. 219, pp. 117-122, 1984.

26 C. Melcher, J. Schweitzer, Liberman, et al., "Temperature dependence of fluorescence decay time and emission spectrum of bismuth germanate," *IEEE Trans Nucl Sci*, vol. NS-32, pp. 529-532, 1985.

27 J. Menefee, C. F. Sweinehart and E. W. O'Dell, "Calcium fluoride as an x-ray and charged particle detector," *IEEE Trans Nucl Sci,* vol. NS-13(1), pp. 720-724, 1966.

28 B. C. Grabmaier, "Crystal scintillators," *IEEE Trans Nucl Sci,* vol. NS-31, pp. 372-376, 1984.

29 D. F. Anderson, "Properties of the high-density scintillator cerium fluoride," *IEEE Trans Nucl Sci,* vol. NS-36, pp. 137-140, 1989.

30 W. W. Moses and S. E. Derenzo, "Cerium fluoride, a new, heavy fast scintillator," *IEEE Trans Nucl Sci,* vol. NS-36, pp. 173-176, 1989.

31 W. W. Moses, S. E. Derenzo, M. J. Weber, et al., "A study of the scintillation decay mechanism of cerium fluoride," Lawrence Berkeley Laboratory Report LBL-27609, 1992, to be submitted to *J Luminescence.*

32 D. F. Anderson, "Cerium fluoride: a scintillator for high-rate applications," *Nucl Instr Meth,* vol. A287, pp. 606, 1990.

33 W. W. Moses and S. E. Derenzo, "The scintillation properties of cerium-doped lanthanum fluoride," *Nucl Instr Meth,* vol. A299, pp. 51-56, 1990.

34 M. Kobayashi, M. Ishii, E. A. Krivandia, et al., "Cerium fluoride, a highly radiation-resistive scintillator," *Nucl Instr Meth,* vol. A302, pp. 443-446, 1991.

35 A. J. Wojtowicz, E. Berman, C. Koepke, et al., "Stochiometric cerium compounds as scintillators part I: CeF_3," *IEEE Trans Nucl Sci,* vol. NS-39, pp. 494-501, 1992.

36 M. Moszynski, C. Gresset, J. Vacher, et al., "Properties of CsF, a fast inorganic scintillator in energy and time spectroscopy," *Nucl Instr Meth,* vol. 179, pp. 271-276, 1981.

37 M. Moszynski, R. Allemand, M. Laval, et al., "Recent progress in fast timing with CsF scintillators in application to time-of-flight positron tomography in medicine," *Nucl Instr Meth,* vol. 205, pp. 239-249, 1983.

38 S. Kubota, J. Ruan(Gen), M. Itoh, et al., "A new type of luminescence mechanism in large band-gap insulators: a proposal for fast scintillation materials," *Nucl Instr Meth,* vol. A289, pp. 253, 1990.

39 H. Grassman, E. Lorenz and H. Moser, "Properties of CsI(Tl) - renaissance of an old scintillation material," *Nucl Instr Meth,* vol. 228, pp. 323-326, 1985.

40 J. Valentine, D. Wehe, G. Knoll, et al., "Temperature dependence of absolute CsI(Tl) scintillation yield," *IEEE Nuclear Science Symposium Conference Record 91CH3100-5,* vol. 1, pp. 176-182, 1991.

41 S. Kubota, S. Sakuragi, S. Hashimoto, et al., "A new scintillation material: pure CsI with 10 nsec decay time," *Nucl Instr Meth,* vol. A268, pp. 275-277, 1988.

42 K. Takagi and T. Fukazawa, "Cerium activated Gd_2SiO_5 single crystal scintillator," *Appl Phys Lett,* vol. 42, pp. 43-45, 1983.

43 M. Dahlbom, M. A. Mandelkern, E. J. Hoffman, et al., "Hybrid mercuric iodide (HgI_2) – gadolinium orthosilicate (GSO) detector for PET," *IEEE Trans Nucl Sci,* vol. NS-32, pp. 533-537, 1985.

44 H. Ishibashi, K. Shimizu, K. Susa, et al., "Cerium doped GSO scintillators and its application to position sensitive detectors," *IEEE Trans Nucl Sci,* vol. NS-36, pp. 170-172, 1989.

45 R. B. Murray, "Use of $Li^6I(Eu)$ as a scintillation detector and spectrometer for fast neutrons," *Nul Instr Meth*, vol. 2, pp. 237-248, 1958.

46 D. E. Persyk, M. A. Schardt, T. E. Moi, et al., "Research on pure sodium iodide as a practical scintillator," *IEEE Trans Nucl Sci*, vol. NS-27, pp. 168-171, 1980.

47 R. V. Jones and J. H. Pollard, "The scintillation properties of cadmium fluoride," *Proc Phys Soc*, vol. 79, pp. 358-365, 1962.

48 P. Schotanus, P. Dorenbos and V. D. Ryzhikov, "Detection of CdS(Te) and ZnSe(Te) scintillation light with silicon photodiodes," *IEEE Trans Nucl Sci*, vol. NS-39, pp. 546-550, 1992.

49 D. J. Ehrich, P. F. Moulton and R. M. Osgood, "Optically pumped Ce:LaF_3 laser at 286 nm," *Optics Lett*, vol. 5(8), pp. 339-340, 1980.

50 P. Schotanus, P. Dorenbos, C. W. E. v. Eijk, et al., "Recent developments in scintillator research," *IEEE Trans Nucl Sci*, vol. NS-36, pp. 132-136, 1989.

51 C. L. Melcher and J. S. Schweitzer, "Cerium-doped lutetium orthosilicate: a fast, efficient new scintillator," *IEEE Trans Nucl Sci*, vol. NS-39, pp. 502-505, 1992.

52 B. B. Shul'gin, L. V. Viktorov, A. R. Volkov, et al., "Scintillation properties of some oxide and fluoride systems," Izd. Ural. Politekhn. Inta., Sverdlovsk, Dep. VINITI Report No. No. 3570, 1990.

53 R. J. Moon, "Inorganic crystals for the detection of high energy particles and quanta," *Phys Rev*, vol. 73, pp. 1210, 1948.

54 W. W. Moses and S. E. Derenzo, "Lead carbonate, a new fast, heavy scintillator," *IEEE Trans Nucl Sci*, vol. NS-37, pp. 96-100, 1990.

55 W. W. Moses, S. E. Derenzo, P. W. Levy, et al., "Further measurements of the scintillation properties of lead carbonate," *IEEE Trans Nucl Sci*, vol. NS-38, pp. 648-653, 1991.

56 M. Minowa, K. Itakura, S. Moriyama, et al., "Measurement of the property of cooled lead molybdate as a scintillator," *Nucl Instr Meth*, vol. A320, pp. 500-503, 1992.

57 G. Blasse, "Energy transfer phenomena in lead sulphate," *Chem Phys Tel*, vol. 35, pp. 299-302, 1975.

58 F. W. K. Firk, "A comparative study of the scintillation response of natural crystals of anglesite ($PbSO_4$) and cerussite ($PbCO_3$)," *Nucl Instr Meth*, vol. A297, pp. 532-533, 1990.

59 W. W. Moses, S. E. Derenzo and P. Schlichta, "Scintillation properties of lead sulfate," *Trans Nucl Sci*, vol. NS-39 (in press), 1992.

60 S. I. Ziegler, J. G. Rogers, S. V, et al., "Characteristics of the new $YaAlO_3$ compared to BGO and GSO," *IEEE Nuclear Science Symposium Conference Record 91CH3100-5*, vol. 1, pp. 158-161, 1991.

61 E. Autrata, P. Schauer and J. Kvapil, "A single crystal of $YAlO_3$-Ce^{3+} as a fast scintillator in SEM," *Scanning*, vol. 5(1), pp. 91-96, 1983.

62 E. Autrata, P. Schauer and J. Kvapil, "A single crystal of YAG – a new fast scintillator in SEM," *J. Phys. E*, vol. 11a, pp. 707-708, 1978.

63 A. R. Kulesskii, A. M. Korovkin, A. V. Kruzhalov, et al., "Radioluminescence and scintillation properties of yttrium and rare-earth silicates," *Zh. Prikl. Spektrosk.*, vol. 48 (4), pp. 650-653, 1988.

64 B. V. Shul'gin, A. R. Kulesskii, A. M. Korovkin, et al., "Spectra and kinetics of pulse cathode luminescence of Y_2SiO_5–Ce, Tb," *Optika i Spektroskopiya,* vol. 68(4), pp. 841-843, 1990.

65 S. E. Derenzo, W. W. Moses, R. Perera, et al., "Prospects for new inorganic scintillators," *IEEE Trans Nucl Sci,* vol. NS-37, pp. 203-208, 1990.

66 S. E. Derenzo, W. W. Moses, J. L. Cahoon, et al., "X-ray fluorescence measurements of 412 inorganic compounds," *IEEE Nuclear Science Symposium Conference Record 91CH3100-5,* vol. 1, pp. 143-147, 1991.

67 L. M. Bollinger and G. E. Thomas, "Measurement of the time dependence of scintillation intensity by a delayed-coincidence method," *Rev Sci Instr,* vol. 32, pp. 1044-1050, 1961.

68 D. Luckey, "A fast inorganic scintillator," *Nucl Instr Meth,* vol. 62, pp. 119-120, 1968.

69 K. G. Tirsell, G. R. Tripp, E. M. Lent, et al., "Sub-nanosecond plastic scintillator time response studies using laser produced X-ray pulsed excitation," *IEEE Trans Nucl Sci,* vol. NS-24, pp. 250-254, 1977.

70 R. E. Chrien and J. D. Strachan, "Selective fast neutron detector," *Rev Sci Instrum,* vol. 51, pp. 1638-1640, 1980.

71 M. Kobayashi, "$PbWO_4$ scintillator at room temperature," *Proceedings of The CRYSTAL 2000 International Workshop on Heavy Scintillators for Scientific and Industrial Applications (this conference),* (Edited by P. Lecoq), Chamonix, France, 1992.

72 V. A. Kachanov, Y. D. Prokoshkin, V. G. Vasilchenko, et al., "Study of characteristics of real-size $PbWO_4$ crystal cells for precise EM-calorimeters to be used at LHC energies," *Proceedings of The CRYSTAL 2000 International Workshop on Heavy Scintillators for Scientific and Industrial Applications (this conference),* (Edited by P. Lecoq), Chamonix, France, 1992.

73 S. E. Derenzo, W. W. Moses, S. C. Blankespoor, et al., "Design of a pulsed x-ray system for fluorescent lifetime measurements with a timing resolution of 109 ps," *IEEE Nuclear Science Symposium Conference Record (in press),* 1992.

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
TECHNICAL INFORMATION DEPARTMENT
BERKELEY, CALIFORNIA 94720