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Fast and Radiation Hard Inorganic Scintillators for Future HEP Experiments

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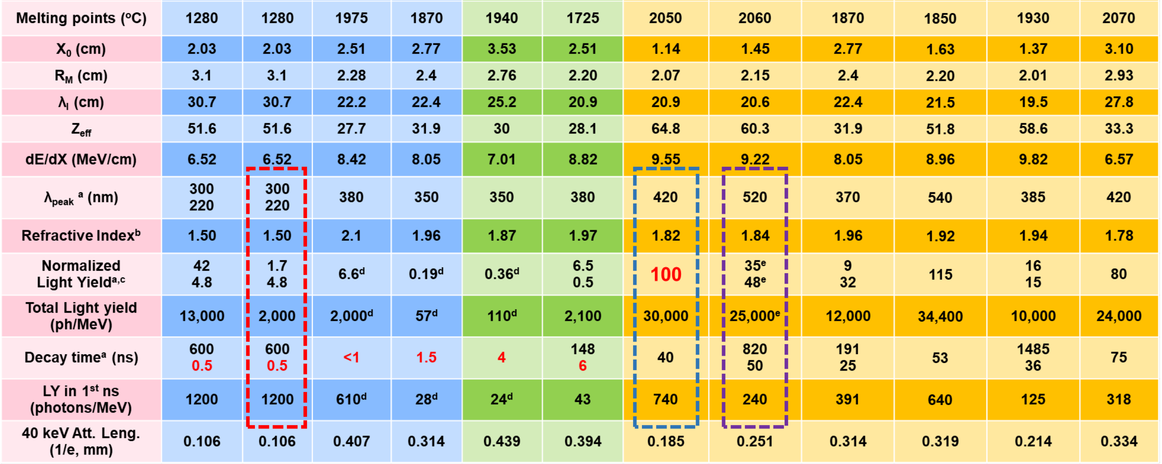
Abstract. Future HEP experiments at the energy and intensity frontiers require fast and ultrafast inorganic scintillators with excellent radiation hardness to face the challenges of unprecedented event rate and severe radiation environment. We report recent progress in fast and ultrafast inorganic scintillators for future HEP experiments. Examples are LYSO crystals and LuAG ceramics for an ultra-compact shashlik sampling calorimeter for the HL-LHC and the proposed FCC-hh, and yttrium doped BaF$_2$ crystals for the proposed Mu2e-II experiment. Applications for GHz hard X-ray imaging will also be discussed.

1. Introduction

Inorganic scintillators are widely used in the high energy physics (HEP) experiments. Fast and radiation hard scintillators are required to survive the unprecedented harsh radiation environment expected by future HEP experiments at the energy frontier, such as the HL-LHC and Future Hadron Circular Collider (FCC-hh), where up to 500 Grad and 5×10^{18} n_{eq}/cm^2 of one MeV equivalent neutron fluence are expected for the forward calorimeter (EMF, HF) [1]. Ultrafast scintillators are required for future HEP experiments at the intensity frontier, such as Mu2e-II [2], to mitigate pileup. Table I lists optical and scintillation properties of fast and ultrafast inorganic scintillators.

Table 1. Scintillation performance of fast and ultrafast inorganic scintillators.



	BaF$_2$	BaF$_2$:Y	ZnO:Ga	YAP:Yb	YAG:Yb	β-Ga$_2$O$_3$	LYSO:Ce	LuAG:Ce	YAP:Ce	GAGG:Ce	LuYAP:Ce	YSO:Ce
Density (g/cm^3)	4.89	4.89	5.67	5.35	4.56	5.94[1]	7.4	6.76	5.35	6.5	7.2^{f}	4.44
Melting points (°C)	1280	1280	1975	1870	1940	1725	2050	2060	1870	1850	1930	2070
X_0 (cm)	2.03	2.03	2.51	2.77	3.53	2.51	1.14	1.45	2.77	1.63	1.37	3.10
R_M (cm)	3.1	3.1	2.28	2.4	2.76	2.20	2.07	2.15	2.4	2.20	2.01	2.93
λ_I (cm)	30.7	30.7	22.2	22.4	25.2	20.9	20.9	20.6	22.4	21.5	19.5	27.8
Z_{eff}	51.6	51.6	27.7	31.9	30	28.1	64.8	60.3	31.9	51.8	58.6	33.3
dE/dX (MeV/cm)	6.52	6.52	8.42	8.05	7.01	8.82	9.55	9.22	8.05	8.96	9.82	6.57
λ_{peak} ^{a} (nm)	300 220	300 220	380	350	350	380	420	520	370	540	385	420
Refractive Index^{b}	1.50	1.50	2.1	1.96	1.87	1.97	1.82	1.84	1.96	1.92	1.94	1.78
Normalized Light Yield^{a,c}	42 4.8	1.7 4.8	6.6^{d}	0.19^{d}	0.36^{d}	6.5 0.5	100	35^{e} 48^{e}	9 32	115	16 15	80
Total Light yield (ph/MeV)	13,000	2,000	2,000^{d}	57^{d}	110^{d}	2,100	30,000	25,000^{e}	12,000	34,400	10,000	24,000
Decay time^{a} (ns)	600 0.5	600 0.5	<1	1.5	4	148 6	40	820 50	191 25	53	1485 36	75
LY in 1st ns (photons/MeV)	1200	1200	610^{d}	28^{d}	24^{d}	43	740	240	391	640	125	318
40 keV Att. Leng. (1/e, mm)	0.106	0.106	0.407	0.314	0.439	0.394	0.185	0.251	0.314	0.319	0.214	0.334

Cerium doped lutetium yttrium oxyorthosilicate ($Lu_{2(1-x)}Y_{2x}SiO_5$:Ce or LYSO) and lutetium aluminium garnet ($Lu_3Al_5O_{12}$ or LuAG:Ce) show high stopping power, high light output, fast decay time and good radiation hardness against ionization dose and hadrons. LYSO crystals are being used to construct a barrel timing layer (BTL) for the CMS upgrade for the HL-LHC, where 5 Mrad ionization dose, 3×10^{13} charged hadrons/cm^2 and 3×10^{14} 1 MeV equivalent neutrons/cm^2 are expected [3]. They were also proposed for an ultra-compact, radiation hard shashlik calorimeter for the HL-LHC [4]. Yttrium doped barium fluoride crystals (BaF_2:Y) have an ultrafast scintillation component with 0.5 ns decay time and a suppressed slow component [5]. An ultrafast BaF_2:Y total absorption calorimeter is considered by the Mu2e-II experiment [2]. Ultrafast inorganic scintillators may also find applications for GHz hard X-ray imaging [6].

2. Bright, fast and radiation hard LYSO:Ce crystals and LuAG:Ce ceramics

Fig.1 shows the radiation induced absorption coefficient (RIAC) values as a function of (1) integrated dose, (2) proton fluence, and (3) 1 MeV equivalent neutron fluence respectively for LYSO crystal samples. We found that damage induced by protons in LYSO is an order of magnitude larger than that from neutrons, which is due to ionization energy loss in addition to displacement and nuclear breakup. The results show that LYSO:Ce crystals satisfy CMS BTL specification of RIAC < 3 m^{-1} after 4.8 Mrad, 2.5×10^{13} p/cm^2 and 3×10^{14} n$_{eq}$/cm^2 [3].

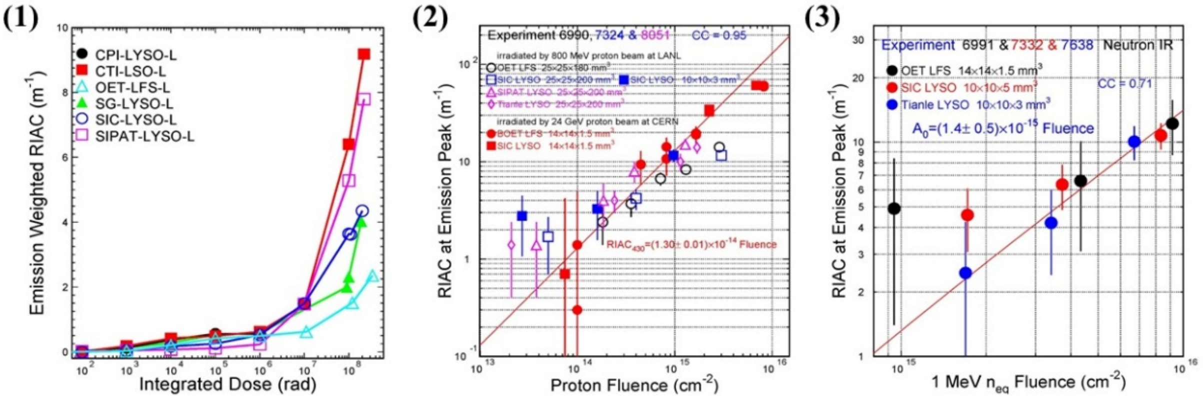


Figure 1. RIAC in LYSO are shown as a function of (1) ionization dose, (2) protons, and (3) neutrons.

Fig. 2 show the RIAC values as a function of (1) 1 MeV equivalent neutron fluence and (2) proton fluence for LuAG:Ce ceramics and compared to LYSO:Ce crystals. We found that LuAG:Ce ceramics shows a factor of two better radiation hardness than LYSO crystals up to 6.7×10^{15} n$_{eq}$/cm^2 and 1.2×10^{15} p/cm^2, so are promising for the FCC-hh. Fig. 2(3) shows that Ca^{2+} co-doping improves the Fast/Total (F/T) ratio, defined as the ratio between the light output in 200 ns and 3,000 ns, to 90%. Because of its excellent radiation hardness [7] and a good match between its excitation and the LYSO:Ce emission [8], LuAG:Ce ceramics may also serve as an effective wavelength shifter for LYSO:Ce crystals for the RADiCAL concept proposed for the HL-LHC and FCC-hh [9].

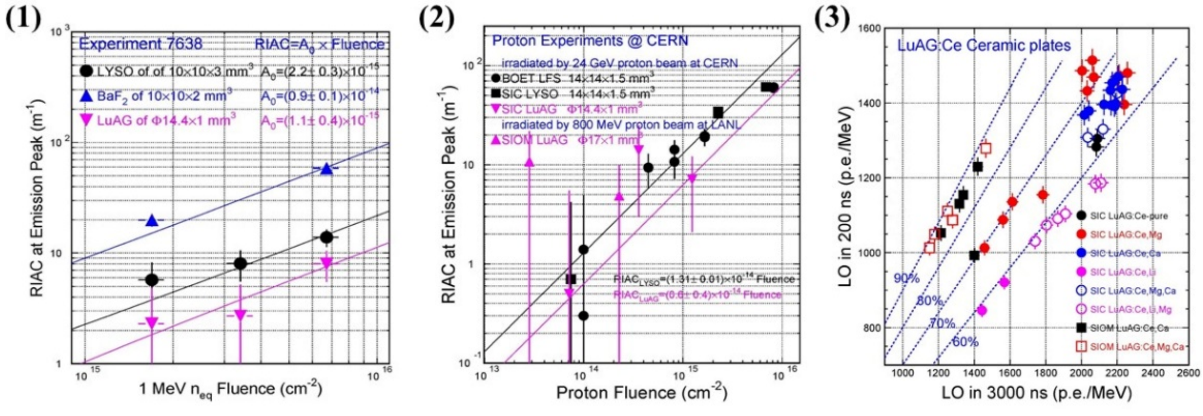


Figure 2. (1-2) Radiation hardness of LuAG:Ce ceramics and (3) slow suppression by co-doping.

3. Ultrafast BaF_2:Y crystals

It is well known that BaF_2 crystals have an ultrafast scintillation component with sub-ns decay time peaked at 220 nm, and a 600 ns slow component peaked at 300 nm with much higher intensity, which would cause pileup in a high rate environment. It is also known that the slow component in BaF_2 crystals can be suppressed either by rare earth doping in crystals [5] or by using a solar blind photodetector [10]. Fig. 3(1) shows nine BaF_2 cylinders of $\Phi 18\times 21$ mm^3 grown at BGRI with different Y^{3+} doping levels. Fig. 3(2) shows the X-ray excited emission (XEL) peaks at 220 and 300 nm for the fast and slow light, showing a reduced slow light intensity for an increased yttrium doping level, while the intensity of the fast emission is maintained. Fig. 3(3) shows the transmittance spectra (solid lines) measured along 21 mm light path for all samples. Fig. 3(4) shows light output as a function of integration time for these samples, confirming a reduced slow component and consistent fast component. Figs. 3(5) and (6) show the response of BaF_2 and BaF_2:Y to septuplet X-ray bunch with 2.83 ns bunch spacing, providing a proof of principle for the ultrafast inorganic scintillator-based front imager for GHz hard X-ray imaging [11]. BaF_2:Y crystals of large size is under development. While yttrium doping in BaF_2 crystals increases its F/S ratio significantly, a solar-blind photodetector is also needed to minimize the pileup for a BaF_2:Y crystal-based ultrafast calorimeter for Mu2e-II [12].

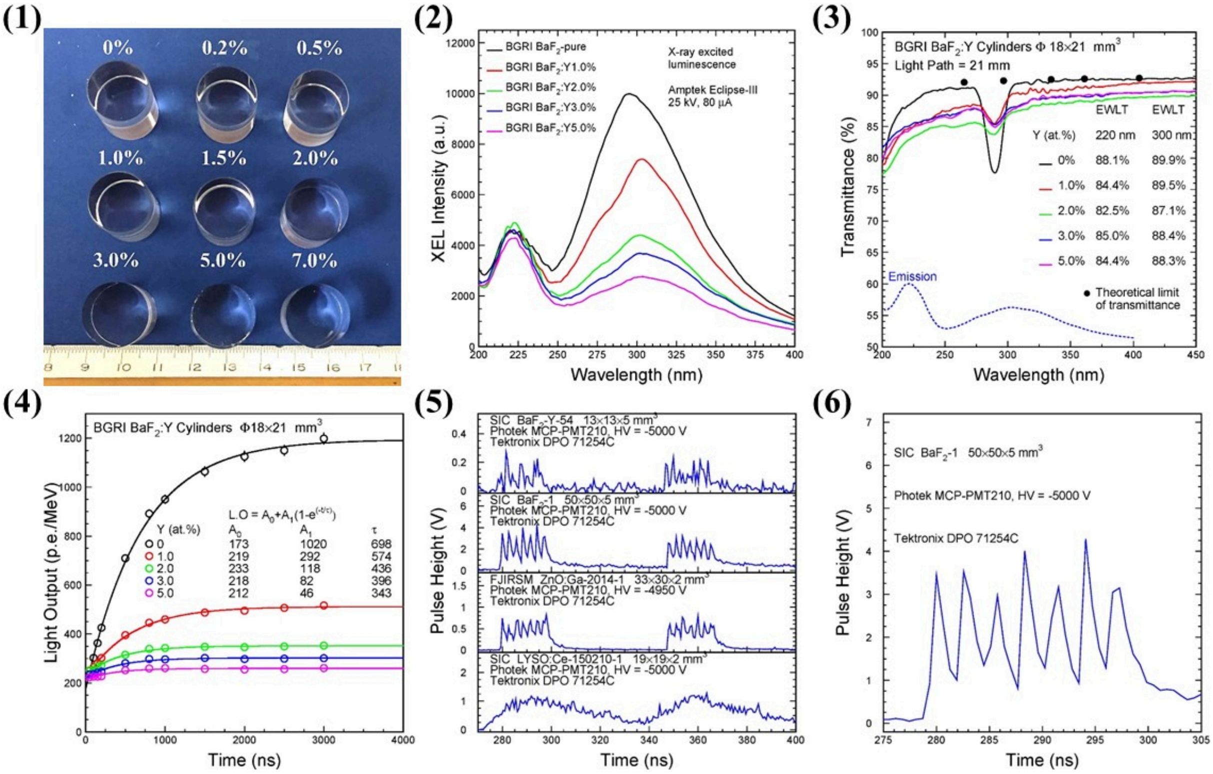


Figure 3. (1-4) Slow component suppression in a set of BaF_2:Y crystals, and (5-6) ultrafast X-ray imaging of BaF_2 and BaF_2:Y crystals to septuplet X-ray bunch with 2.83 ns bunch spacing,.

4. Summary

Bright, fast and radiation hard LYSO:Ce and LuAG:Ce survive up to 10^{15} p/cm^2 and 10^{16} n_{eq}/cm^2, so are promising materials for such a severe radiation environment expected by future HEP experiments at the energy frontier. R&D is on-going to develop these materials for an ultra-compact, radiation hard RADiCAL concept for the HL-LHC and the proposed FCC-hh

Undoped BaF_2 crystals of large size (20 cm) provide ultrafast light with 0.5 ns decay time and a good radiation hardness up to 130 Mrad. Yttrium doping suppresses its slow light and promises an ultrafast inorganic scintillator with much reduced slow contamination. R&D is on-going to develop both yttrium doped BaF_2 crystals of large size and solar-blind VUV photodetectors for future HEP experiments at the intensity frontier, such as Mu2e-II.

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