Nuclear Inst. and Methods in Physics Research, A 992 (2021) 165043

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

UV–Visible reflectance of common light reflectors and their degradation after an ionization dose up to 100 Mrad

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ARTICLE INFO

Keywords:
Reflector
Scintillator
Reflectance spectrum
Ionization dose
Radiation hardness

ABSTRACT

Light reflectors are widely used to enhance scintillation light collection. Their enhancement level depends on the reflector's reflectance at the scintillator's emission wavelength. We report UV–Visible reflectance spectra, relative to $BaSO_4$, for several common reflectors. Also reported is their radiation hardness against an ionization dose up to 100 Mrad. The results of this investigation provide a reference for applications of these reflectors in a severe radiation environment.

1. Introduction

Scintillators are widely used in high energy physics (HEP) calorimeters [1–4]. In HEP, as well as nuclear medicine and homeland security applications [5–9], reflectors are used as wrapping material to enhance light collection efficiency for scintillation light. The level of the enhancement depends on the reflector's reflectance at the scintillator's emission wavelength [6,8,10,11]. Both reflectors and scintillators may suffer from radiation damages induced by ionization dose and/or hadrons expected in a radiation environment, causing a degraded light output for scintillator-based detectors [12,13]. Future HEP calorimeters at the high luminosity-large hadron collider with an integrated luminosity of 3,000 fb^{-1}, for example, will be operated in a severe radiation environment, where up to 100 Mrad of ionization dose and 10^{15} hadrons/cm^2 fluence are expected [13]. While radiation induced damage in inorganic scintillators has been intensively investigated for an ionization dose up to 340 Mrad [14], a proton fluence up to $3\times10^{15}/cm^2$ [15], and a 1 MeV equivalent neutron fluence up to $9\times10^{15}/cm^2$ [16], only limited investigations were reported on radiation damage in reflectors [17–19].

We report results of an investigation on relative reflectance spectra for six common reflectors: aluminum foil, aluminized mylar film, 3M™ enhanced specular reflector film (ESR), Tyvek paper and Polytetrafluoroethylene (PTFE) films, and their radiation damage after an ionization dose of up to 100 Mrad.

2. Samples and measurements

Fig. 1 shows a reflector sample assembly (top), six reflector samples and their thickness (bottom). While most samples are of single layer with various thickness, the PTFE film samples are of five and eight layers with 25 μm thickness per layer and no glue between them. These samples were placed on the top of a 50 μm thick steel base, which is attached to a PTFE plug coated with $BaSO_4$ as the reference.

Fig. 2 shows the setup used for measuring the relative reflectance spectra. The plug with a sample attached was inserted into a 2.5 inch integrating sphere in a HITACHI U3210 UV/Vis spectrophotometer's large sample compartment. While aluminum foil, aluminized mylar and ESR are featured with specular reflection, Tyvek and PTFE have diffuse reflection [10]. The light collection system was designed to collect both specular and diffuse reflected light with a 10° angle between the incident beam and the normal direction of the sample to minimize the leakage of spectral reflected light. A Hamamatsu photomultiplier (PMT) located at the bottom of the integrating sphere was used to collect response light. The response light measured with a reflector sample on the top of the $BaSO_4$ reference plug to that without provided the reflectance spectrum relative to $BaSO_4$ for the reflector sample. The systematic uncertainty was determined to be about 1% between 250 and 800 nm by repeated measurements, which was increased to about 7% at 220 nm due to a lower signal-to-noise ratio below 250 nm.

Gamma-ray irradiations were carried out at the Total Ionization Dose (TID) facility of Jet Propulsion Laboratory (JPL), where a group of high intensity ^{60}Co sources provided a dose rate up to 1 Mrad/h. All reflectors were irradiated in two steps for 10 and 90 Mrad at 0.18 and 1 Mrad/h respectively to reach a cumulated dose of 100 Mrad. The PTFE film samples turned yellowish and broke into pieces after 100 Mrad. Consequently, the resulting irradiation data are shown only for 10 Mrad irradiation for PTFE films.

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https://doi.org/10.1016/j.nima.2021.165043
Received 15 December 2020; Received in revised form 8 January 2021; Accepted 8 January 2021
Available online 11 January 2021
0168-9002/© 2021 Published by Elsevier B.V.

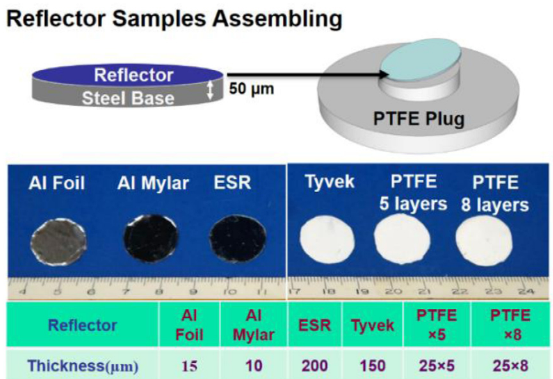

Fig. 1. A sample assembly (top) and six reflector samples and their thickness (bottom).

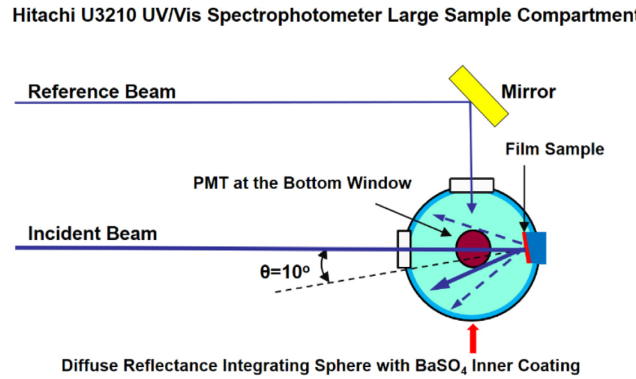

Fig. 2. The setup used to measure the relative reflectance spectrum with a Hitachi U3210 UV/VIS spectrophotometer.

Table 1
Initial EWRR values relative to $BaSO_4$ for LYSO, BGO and BaF_2 scintillation crystals.

EWRR	LYSO (%)	BGO (%)	BaF_2 @220 nm[a] (%)	BaF_2@300 nm[b] (%)
Al Foil	76.5 ± 1.0	80.4 ± 1.0	56.3 ± 7.0	70.5 ± 1.0
Al Mylar	75.2 ± 1.0	79.8 ± 1.0	43.6 ± 7.0	66.7 ± 1.0
ESR	78.5 ± 1.0	87.9 ± 1.0	–	–
Tyvek	96.7 ± 1.0	96.7 ± 1.0	71.9 ± 7.0	89.5 ± 1.0
PTFE (5 layers)	97.2 ± 1.0	95.6 ± 1.0	107.8 ± 7.0	103.3 ± 1.0
PTFE (8 layers)	100.4 ± 1.0	99.0 ± 1.0	106.7 ± 7.0	105.4 ± 1.0

[a]Fast scintillation with emission peak at 220 nm of BaF_2.
[b]Slow scintillation with emission peak at 300 nm of BaF_2.

3. Experimental results

3.1. Initial relative reflectance spectrum

Fig. 3(a) and (b) show initial relative reflectance spectra for the aluminum foil, aluminized mylar film, 3M™ ESR film and Tyvek paper, and the PTFE films, respectively. Also shown in the figures are the X-ray excited emission spectra of BaF_2, $Bi_4Ge_3O_{12}$ (BGO) and $Lu_{2(1-x)}Y_{2x}SiO_5Ce$ (LYSO:Ce) crystals. Table 1 lists the numerical values of the emission weighted relative reflectance (EWRR) defined as:

$$EWRR = \frac{\int emission(\lambda) \cdot reflectance(\lambda)\, d\lambda}{\int emission(\lambda) d\lambda}, \quad (1)$$

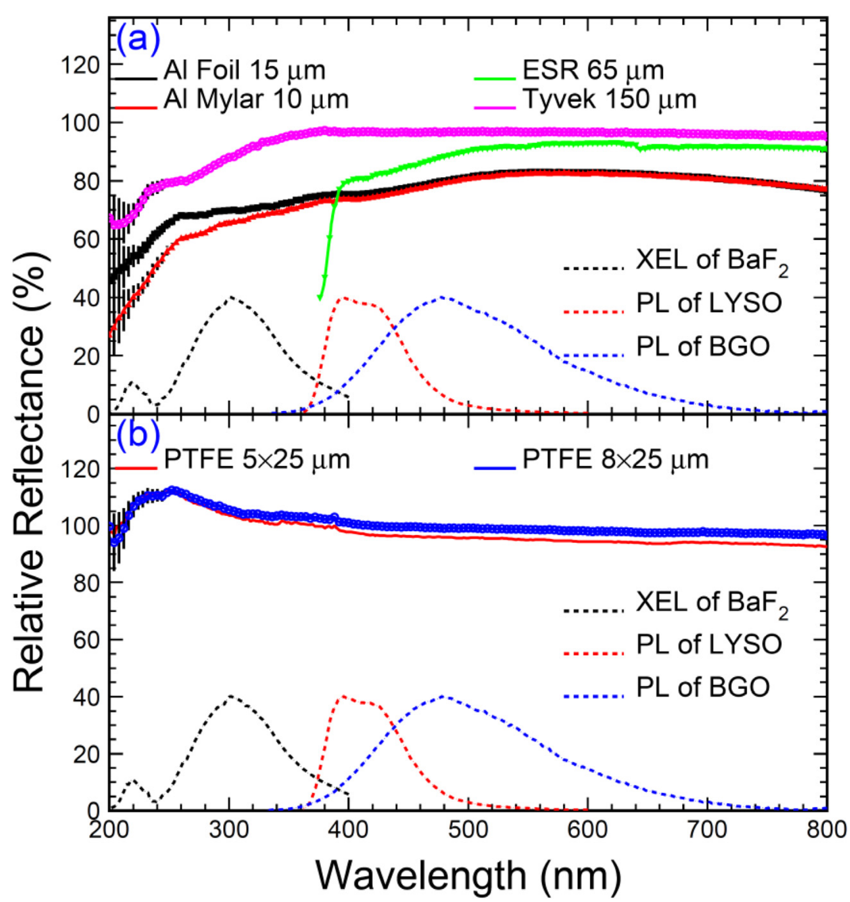

Fig. 3. The initial relative reflectance spectra for (a) aluminum foil, aluminized mylar, ESR and Tyvek, and (b) PTFE films of five and eight layers).

Table 2
Normalized losses (%) of the EWRR values after Gamma-ray irradiations for all samples.

	Reflectors	Ionization Dose (rad)	LYSO	BGO	BaF_2@220 nm[a]	BaF_2@300 nm[b]
Normalized EWRR Loss (%)	Al Foil	10^7	2.2 ± 1.6	1.6 ± 1.6	5 ± 11	3.0 ± 1.6
		10^8	4.4 ± 1.6	3.5 ± 1.6	4 ± 11	4.5 ± 1.6
	Al Mylar	10^7	0.8 ± 1.6	0.1 ± 1.6	3 ± 11	0.0 ± 1.6
		10^8	13.3 ± 1.6	14.3 ± 1.6	3 ± 11	6.6 ± 1.6
	ESR	10^7	1.4 ± 1.6	0.0 ± 1.6	–	–
		10^8	9.8 ± 1.6	2.6 ± 1.6	–	–
	Tyvek	10^7	1.8 ± 1.6	0.1 ± 1.6	33 ± 11	13.9 ± 1.6
		10^8	14.4 ± 1.6	7.3 ± 1.6	55 ± 11	38.9 ± 1.6
	PTFE (5 layers)	10^7	6.3 ± 1.6	6.6 ± 1.6	46 ± 11	10.6 ± 1.6
	PTFE (8 layers)	10^7	3.4 ± 1.6	3.3 ± 1.6	38 ± 11	8.2 ± 1.6

[a]Fast scintillation with emission peak at 220 nm of BaF_2.
[b]Slow scintillation with emission peak at 300 nm of BaF.

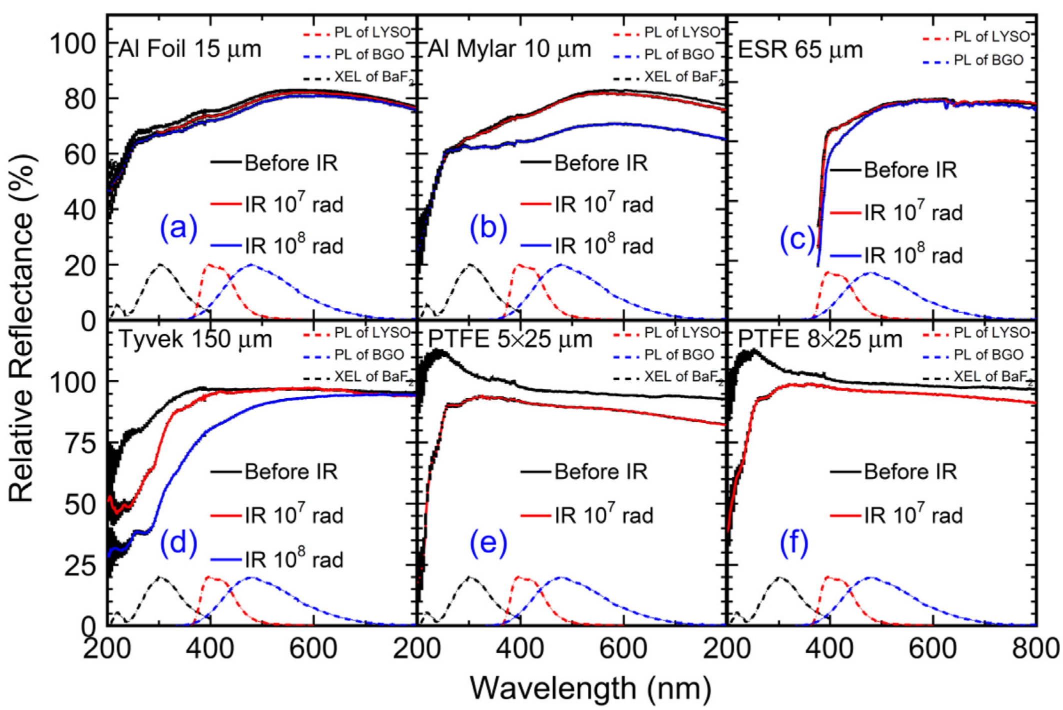

Fig. 4. The relative reflectance spectra measured before and after gamma-ray irradiations for (a) aluminum foil, (b) aluminized mylar, (c) ESR film, (d) Tyvek paper, (e) PTFE films of five layers and (f) PTFE films of eight layers.

where the emission(λ) is the emission spectrum of LYSO:Ce, BGO and the fast and slow component of BaF_2, and the reflectance (λ) is the relative reflectance spectrum of the reflector sample. The EWRR value provides a numerical representation of the relative reflectance across the entire emission spectrum.

The relative reflectance of the aluminum foil and the aluminized mylar film degrades below 250 nm, indicating that they do not match well with the VUV luminescence from e.g. BaF_2. A strong absorption below 390 nm is observed for the ESR film, which is caused by the fluorescence excitation in ESR [11], indicating that ESR does not match with scintillators UV luminescence, such as BaF_2 and undoped CsI. Tyvek paper shows a good relative reflectance between 370 to 800 nm, matching well with LYSO and BGO. PTFE films show the highest relative reflectance between 200 to 800 nm, indicating that they are excellent reflectors for almost all scintillators. This result is consistent with the previous publication [11].

3.2. Relative reflectance spectrum after irradiations

Fig. 4 shows relative reflectance spectra for six samples before and after gamma-ray irradiations of up to 100 Mrad. Table 2 lists the corresponding numerical values of the normalized EWRR loss. Although with the lowest initial relative reflectance, the aluminum foil shows the smallest degradation in the relative reflectance between 200 to 800 nm after irradiations up to 100 Mrad, indicating its excellent stability against gamma-rays up to 100 Mrad. No degradation is observed in the aluminized mylar film after 10 Mrad, and between 200 to 250 nm after 100 Mrad. Significant degradation, however, is observed between 250 and 800 nm in the aluminized mylar film. The ESR film shows no degradation in the relative reflectance after 10 Mrad, and between 500 to 800 nm after 100 Mrad. Significant degradation, however, is observed between 200 and 500 nm in the ESR film after 100 Mrad. Tyvek paper shows a good radiation hardness between 400 to 800 nm after 10 Mrad, while degradation is observed between 200 to 400 nm and between 200 to 700 nm after 100 Mrad. PTFE films show significant degradation in relative reflectance between 200 to 800 nm after 10 Mrad, indicating its poor radiation hardness against ionization dose.

Fig. 5 shows the normalized EWRR values as a function of the integrated dose for LYSO (a), BGO (b) and BaF_2's fast (200 nm, c) and slow (300 nm, d) scintillation components. It illustrates that the aluminum

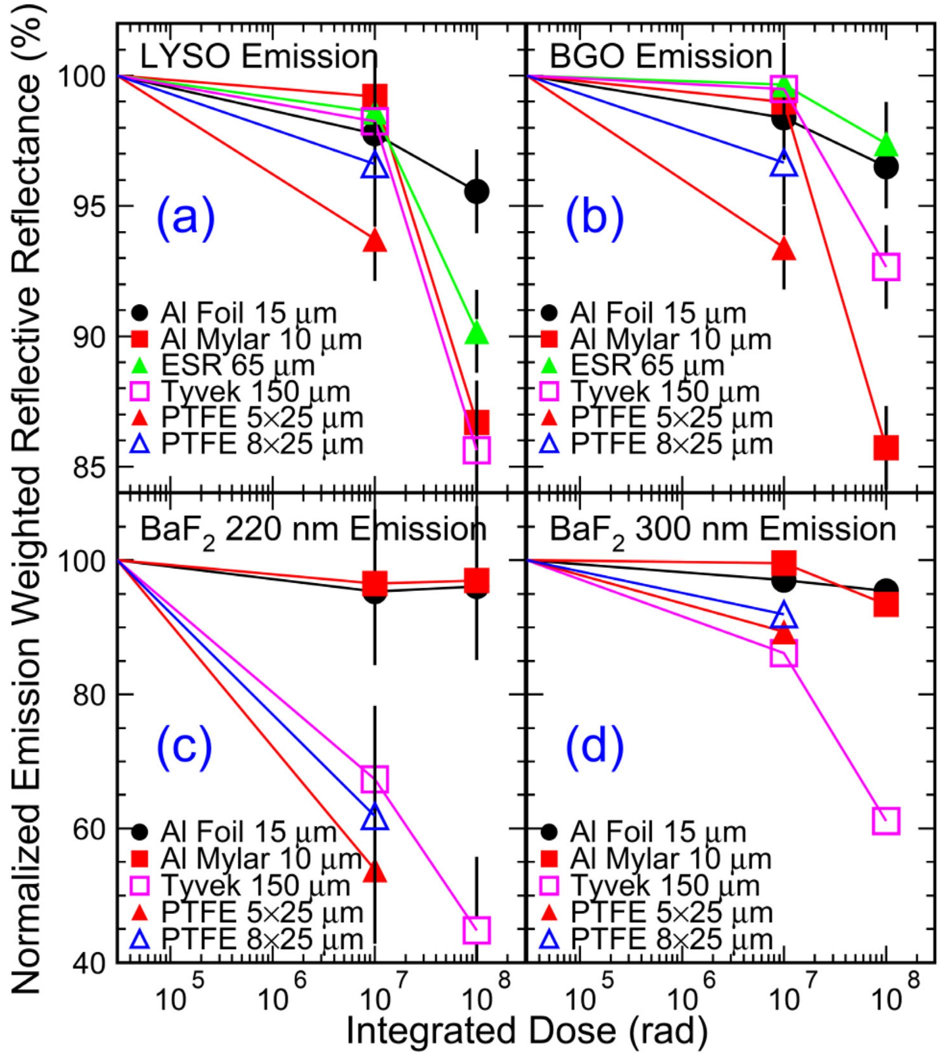

Fig. 5. Normalized emission weighted relative reflectance is shown as a function of the integrated dose for (a) LYSO, (b) BGO, (c) BaF_2 fast scintillation at 220 nm and (d) BaF_2 slow scintillation at 300 nm.

foil and ESR film have excellent radiation hardness against gamma-rays used as wrapping materials for LYSO and BGO. Considering the absolute EWRR values, ESR is the best choice for both LYSO and BGO in a severe radiation environment. For BaF_2 crystals, aluminum foil and aluminized mylar have good radiation hardness although their initial EWRR values are lower than multilayers PTFE films. PTFE thus is a good choice for BaF_2 crystal used in a low radiation environment, while aluminum foil and aluminized Mylar are better choices for BaF_2 in a severe radiation environment.

4. Summary

We measured the relative reflectance spectrum and its radiation hardness against ionization dose for the following commonly used reflectors: aluminum foil, aluminized mylar film, ESR film, Tyvek paper and multilayer PTFE films. The result shows that multilayer PTFE films show the best relative reflectance between 200 to 800 nm, perfect for all inorganic scintillators. PTFE films, however, show poorer radiation hardness against gamma-rays as compared to aluminum foil and ESR film. Both aluminum foil and ESR film, however, have their weakness. Aluminum foil has a relatively low reflectance. ESR film has a strong absorption below 390 nm. There is no perfect reflector with high reflectance in a wide spectrum range and a good radiation hardness. The selection of reflector for inorganic scintillators thus depends on the emission wavelength and radiation environment. Trade-off between the reflectance and the radiation hardness is needed for some applications.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the U.S. Department of Energy, Office of High Energy Physics program under Award Number DE-SC0011925, National Natural Science Foundation of China under Grant 11775120, 11535010 and Natural Science Foundation of Tianjin City under Grant 18JCYBJC17800.

References

[1] M. Oreglia, et al., Study of the reaction $\psi' \to \gamma\gamma J/\psi$, Phys. Rev. D 25 (1982) 2259.

[2] The L3 Collaboration, The construction of the L3 experiment, Nucl. Instrum. Methods Phys. Res. A 289 (1990) 35–102.

[3] The *BaBar* Collaboration, BaBar Technical Design Report, SLAC-R-95-457, 1995.

[4] Compact Muon Solenoid Technical Proposal, CERN/LHCC 94-38, 1994.

[5] M. Yamashita, T. Doke, K. Kawasaki, J. Kikuchi, S. Suzuki, Scintillation response of liquid Xe surrounded by PTFE reflector for gamma rays, Nucl. Instrum. Methods Phys. Res. A 535 (2004) 692–698.

[6] N. Orita, H. Murayama, H. Kawai, N. Inadama, T. Tsuda, Three-dimensional array of scintillation crystals with proper reflector arrangement for a depth of interaction detector, IEEE Trans. Nucl. Sci. 52 (2005) 8–14.

[7] W.S. Rabinovich, R. Mahon, C.I. Moore, M.S. Ferraro, M.R. Suite, H.R. Burris, et al., Optical Scintillation Measurements in a Desert Environment 2: Retro-reflector Links, Free-Space and Atmospheric Laser Communications Xi, 8162, 2011.

[8] R. Scafe, R. Pani, R. Pellegrini, M.N. Cinti, P. Bennati, S. Lo Meo, MgO reflectance data for Monte Carlo simulation of LaBr3:Ce scintillation crystals, Nucl. Instrum. Methods Phys. Res. A 701 (2013) 44–53.

[9] J.W. Son, M.S. Lee, J.S. Lee, A depth-of-interaction PET detector using a stair-shaped reflector arrangement and a single-ended scintillation light readout, Phys. Med. Biol. 62 (2017) 465–483.

[10] M. Janecek, W.W. Moses, Optical reflectance measurements for commonly used reflectors, IEEE Trans. Nucl. Sci. 55 (2008) 2432–2437.

[11] M. Janecek, Reflectivity spectra for commonly used reflectors, IEEE Trans. Nucl. Sci. 59 (2012) 490–497.

[12] N. Atanov, V. Baranov, J. Budagov, Y.I. Davydov, V. Glagolev, V. Tereshchenko, et al., Design and status of the Mu2e crystal calorimeter, IEEE Trans. Nucl. Sci. 65 (2018) 2073–2080.

[13] B. Bilki, C. Collaboration, CMS forward calorimeters phase II upgrade, in: 16th International Conference on Calorimetry in High Energy Physics (Calor 2014), Giessen, Germany, 2015, p. 587.

[14] F. Yang, L.Y. Zhang, R.-Y. Zhu, Gamma-ray induced radiation damage up to 340 mrad in various scintillation crystals, IEEE Trans. Nucl. Sci. 63 (2016) 612–619.

[15] C. Hu, F. Yang, L.Y. Zhang, R.-Y. Zhu, J. Kapustinsky, R. Nelson, et al., Proton-induced radiation damage in BaF_2, LYSO, and PWO crystal scintillators, IEEE Trans. Nucl. Sci. 65 (2018) 1018–1024.

[16] C. Hu, F. Yang, L.Y. Zhang, R.-Y. Zhu, J. Kapustinsky, M. Mocko, et al., Neutron-induced radiation damage in LYSO, BaF_2, and PWO crystal scintillators, IEEE Trans. Nucl. Sci. 67 (2020) 1086–1092.

[17] K.C. Peng, S.K. Sahu, H.C. Huang, K. Ueno, Y.H. Chang, C.H. Wang, et al., Measurement of radiation damage on an optical reflector, Nucl. Instrum. Methods Phys. Res. A 384 (1997) 544–546.

[18] H. Liu, Q. Wei, S.Y. He, D. Zhao, Proton radiation effects on optical constants of Al film reflector, Chin. Phys. 15 (2006) 1086–1089.

[19] J.K. Yao, J.Y. Ma, C. Xiu, Z.X. Fan, Y.X. Jin, Y.A. Zhao, et al., Laser-induced damage of TiO_2/SiO_2 high reflector at 1064 nm, J. Appl. Phys. 103 (2008) 083103.