Neutron and Proton-Induced Radiation Damage in LuAG Scintillating Ceramics

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2020 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC) | 978-1-7281-7693-2/20/$31.00 ©2020 IEEE | DOI: 10.1109/NSS/MIC42677.2020.9507969

***Abstract*–Because of its potential low cost, bright and fast LuAG scintillating ceramics have attracted a broad interest in the HEP community. One crucial issue for its application at future high energy colliders is its radiation hardness against hadrons, including both neutrons and protons. LuAG ceramics were irradiated at LANSCE and CERN up to 6.7×10^{15} n$_{eq}$/cm^2 and 1.2×10^{15} p/cm^2 respectively, and are found to have a factor of two better radiation hardness than LYSO crystals. Ca^{2+} co-doping in LuAG ceramics improves the fast to total ratio and the radiation hardness against hadrons.**

I. Introduction

BECAUSE of its bright and fast scintillation light and potential low cost cerium-doped $Lu_3Al_5O_{12}$ scintillating ceramics (LuAG:Ce) have attract a broad interest in the high-energy physics (HEP) community. One crucial issue is its radiation hardness against hadrons in a severe radiation environment expected at future hadron colliders, such as the High-Luminosity Large Hadron Collider (HL-LHC) and the proposed Future Circular Hadron Collider (FCC-hh). We report radiation damage in Mg^{2+} (and Ca^{2+}) co-doped LuAG:Ce ceramics irradiated up to 6.7×10^{15} n$_{eq}$/cm^2 and 1.2×10^{15} p/cm^2 at the Weapons Neutron Research facility of Los Alamos Neutron Science Center (LANSCE) and CERN PS-IRRAD proton facility, and compare to LYSO crystals.

II. Experimental Details

Fig. 1 (Left) shows the proton and neutron irradiation experiment sites respectively in the blue room of LANSCE by 800 MeV protons with a FWHM diameter of about 25 mm and the Target 4 area (East Port) of LANSCE by neutrons of a broad energy spectrum. Proton irradiation experiment was also carried out at the CERN PS-IRRAD Proton Facility by 24 GeV protons with a FWHM diameter of about 12 mm. For the proton irradiation experiments LuAG ceramic samples were directly face the beam with fluence measured by dedicated sensors. Fig. 1 (Right) shows the sample location at about 1.2 m away from the neutron production target. The 1 MeV equivalent neutron fluence was calculated by using the MCNPX simulation package developed at LANL.

Manuscript received November 23, 2020. This work was supported in part by the US Department of Energy Grants DE-SC0011925 and DE-AC52-06NA25396.

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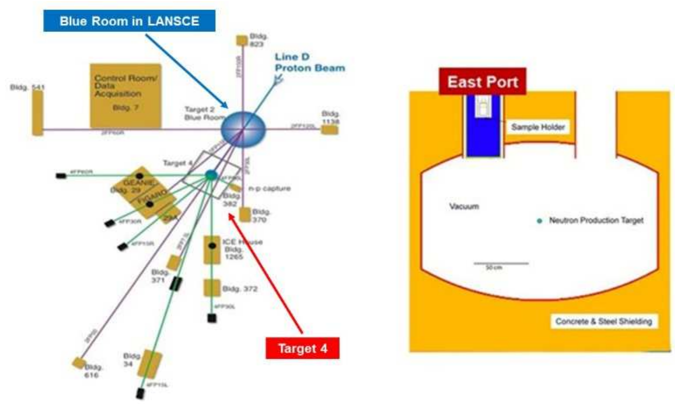

Fig. 1. The proton and neutron irradiation experiment sites in the blue room and the East Port of the Target 4 area of LANSCE (Left), and the sample location in the East Port (Right).

Three Mg^{2+} co-doped LuAG:Ce ceramic samples n-1, n-2, and n-3 of Φ14.4×1 mm^3 were irradiated at the East Port by neutrons with a 1 MeV equivalent neutron fluence of 1.7, 3.4, and 6.7×10^{15} cm^{-2}, respectively. The uncertainty of the neutron fluence is about 10%. Three Mg^{2+} co-doped LuAG:Ce ceramic samples p-1, p-2, and p-3 of Φ14.4×1 mm^3 were irradiated at CERN with a fluence of 7.1×10^{13}, 3.6×10^{14}, and 1.2×10^{15} p/cm^2, respectively. Two Ca^{2+} and Mg^{2+} co-doped LuAG:Ce ceramics p-4 and p-5 of Φ17×1 mm^3 were irradiated at the blue room of LANSCE by 800 MeV protons with a fluence of 2.4×10^{13} and 2.3×10^{14} p/cm^2, respectively. The uncertainties of the proton fluence at CERN and LANSCE are 7% and 10%, respectively.

Their scintillation performance was measured at Caltech HEP crystal lab before and after irradiation. Transmittance was measured by using a Hitachi U3210 spectrophotometer with 0.2% precision. Light output was measured by using a Hamamatsu R2059 PMT with a grease coupling between the sample and the PMT for 0.511 MeV γ-rays from a ^{22}Na source with a coincidence trigger. The systematic uncertainty of the light output measurement is about 1%.

III. Results and Discussion

Fig. 2 shows transmittance spectra for the LuAG ceramic samples n-3 (top) and p-3 (bottom) before and after a 1 MeV equivalent neutron fluence of 6.7×10^{15} n$_{eq}$/cm^2 at LANSCE and a proton fluence of 1.2×10^{15} p/cm^2 at CERN, respectively. Very small losses in transmittance were observed, showing excellent radiation hardness of the LuAG:Ce ceramics against both neutrons and protons.

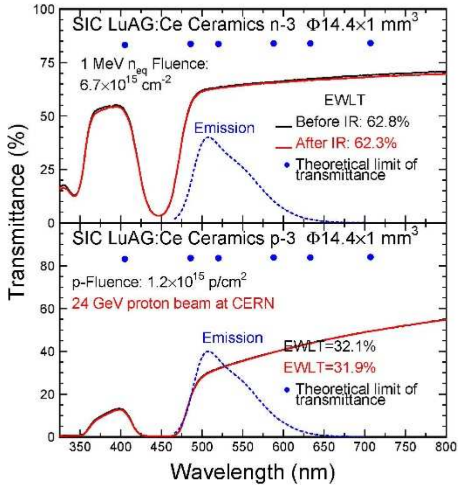

Fig. 2. Transmittance spectra for the LuAG ceramic samples n-3 (top) and p-3 (bottom) before and after a 1 MeV equivalent neutron fluence of 6.7×10^{15} n_{eq}/cm^2 at LANSCE and a proton fluence of 1.2×10^{15} p/cm^2 at CERN, respectively.

Fig. 3 shows light output as a function of integration time for the LuAG ceramic samples n-3 (top) and p-5 (bottom) before and after a 1 MeV equivalent neutron fluence of 6.7×10^{15} n_{eq}/cm^2 and a proton fluence of 2.3×10^{14} p/cm^2 at LANSCE, respectively. About 90% light output remains for both samples, confirming their excellent radiation hardness. We note that the fast to total ratio (F/T), defined as the ratio between light output in 200 ns and 3,000 ns gate, is not changed. We also note that the Mg^{2+} co-doping improves light output, and the Ca^{2+} and Mg^{2+} co-doping improves F/T.

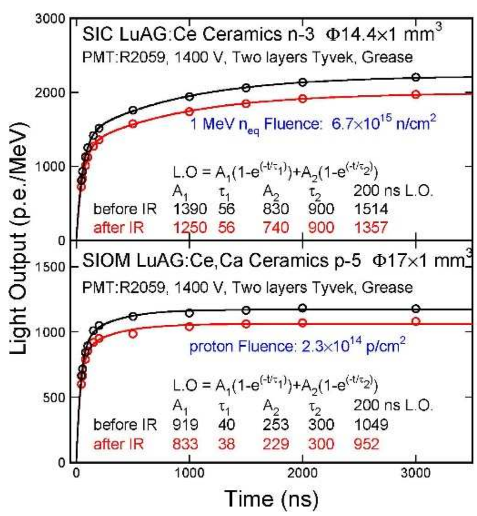

Fig. 3. Light output is shown as a function of integration time for LuAG ceramic samples n-3 (top) before and after a 1 MeV equivalent neutron fluence of 6.7×10^{15} n_{eq}/cm^2 and p-5 (bottom) before and after a proton fluence of 2.3×10^{14} p/cm^2 at LANSCE.

Fig. 4 shows the radiation induce absorption (RIAC) values as a function of neutron fluence for LYSO crystals and LuAG ceramic samples irradiated at the East Port of LANSCE. The RIAC value of the LuAG ceramics against neutrons is about a factor of two smaller than that of LYSO crystals. Fig. 5 shows the RIAC values as a function of proton fluence for LYSO/LFS crystals and LuAG ceramic samples irradiated at CERN. Similar to the neutron irradiation experiment, the radiation hardness of LuAG ceramics against protons is also about a factor of two smaller than that of LYSO crystals. LuAG ceramic thus can be considered as a promising scintillator for future HEP experiments in a severe radiation environment, such as the HL-LHC and the proposed FCC-hh.

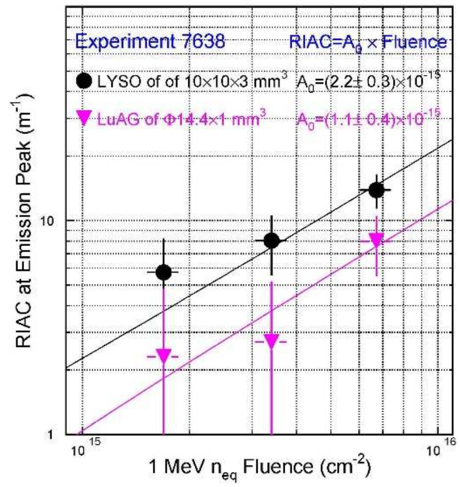

Fig. 4. RIAC as a function of 1 MeV equivalent neutron fluence for LYSO crystals and LuAG ceramics irradiated in the East Port of LANSCE.

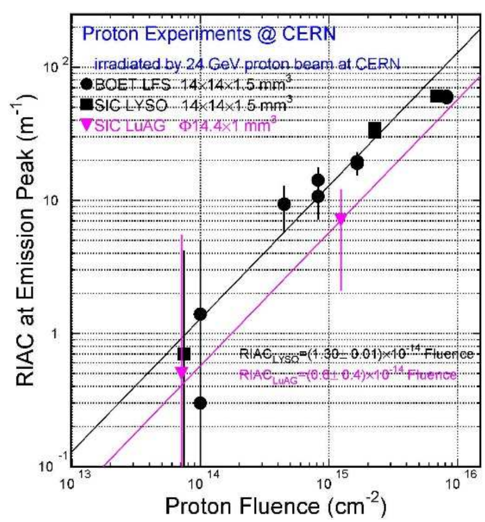

Fig. 5. RIAC as a function of proton fluence for the BOET LFS, SIC LYSO crystal and SIC LuAG ceramic samples irradiated at CERN.

IV. Summary

Ca^{2+} and Mg^{2+} co-doped LuAG:Ce ceramic samples were fabricated and irradiated up to 6.7×10^{15} n_{eq}/cm^2 and 1.2×10^{15} p/cm^2 respectively at LANSCE and CERN. Mg^{2+} co-doping in LuAG ceramics improves light output, while Ca^{2+} and Mg^{2+} co-doping improves F/T ratio. The radiation hardness of LuAG ceramics against both neutrons and protons is about a factor of two better than that of LYSO crystals. With 90% light output remains in 1 mm thick samples after neutron and proton fluences of up to 6.7×10^{15} n_{eq}/cm^2 and 1.2×10^{15} p/cm^2 respectively, LuAG ceramic is a promising scintillator for future HEP experiments in a severe radiation environment, such as the HL-LHC and FCC-hh. R&D will continue to develop co-doped LuAG:Ce,Ca ceramics to further improve its optical quality, F/T ratio and radiation hardness.