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Radiation damage of heavy crystalline detector materials by 24 GeV protons

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ABSTRACT

Samples of three heavy crystalline materials: $PbWO_4$, $Bi_4Si_3O_{12}$, and PbF_2 were irradiated in a high-intensity 24 GeV proton beam at the CERN PS to fluencies of 3.8×10^{13} protons/cm^2. The optical transmission radiation damage was measured and all crystals show a shift of the cutoff in the transmission spectrum that is not observed when the crystals are irradiated with γ radiation. This shift of the cutoff under proton irradiation seems to be a general property of the heavy crystalline materials. A mechanism for this proton-induced transmission damage is discussed.

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1. Introduction

Heavy crystalline materials are widely used in electromagnetic calorimeters in high-energy physics experiments and are considered for future experiments. For example, lead tungstate, $PbWO_4$, (PWO) crystals are used in the CMS electromagnetic calorimeter (ECAL) and in the ALICE photon detector at the LHC [1]; lead fluoride, PbF_2, which is a Cherenkov radiator, is used for the total absorption homogenous calorimeters of the A4 experiment at the Mainz electron accelerator facility MAMI [2]. PWO is used in the electromagnetic calorimeter of the PANDA detector currently being built at FAIR [3], and bismuth silicate, $Bi_4Si_3O_{12}$ (BSO), which is a structural analog of the widely used bismuth germanate (BGO), is considered for the dual readout of the scintillation and Cherenkov light generated by the shower in electromagnetic and hadron calorimeters [3].

The effects of γ radiation on the optical transmission of all these crystals have been studied in detail [2,4–6], and it has been shown that degradation in optical transmission is related to color centers produced at defects created during the growth of the crystal. Furthermore, it has been shown that by optimizing the details of the crystal production process, the optical transmission damage can be moderated, as was achieved by the CMS collaboration, which successfully improved the radiation tolerance of PWO crystals for the CMS ECAL [7].

As anticipated by simulation and confirmed by the recent results, the hadron-induced radiation damage can also significantly affect the performance of an electromagnetic calorimeter at modern high-luminosity machines. The first measurements of the damage effects in PWO crystals irradiated with 24 GeV protons [8,9] have shown significant changes in the crystal's optical transmission with fluencies larger than 10^{13} protons/cm^2. With the recent progress in the performance of the LHC machine, which is currently delivering instantaneous luminosities up to 6.6×10^{33} cm^{-2} s^{-1}, such fluencies can now be expected in the $\eta > 2.5$ regions of LHC detectors in the near future, and the damage to the PWO crystals due to hadrons is expected to be measureable *in situ*.

At wavelengths above 450 nm, hadron-induced transmission damage of PWO crystals is similar to that observed after γ irradiation, but there are additional features at shorter wavelengths. These are a shift in the transmission spectrum cutoff to longer wavelengths by several tens of nanometers, and a very slow spontaneous recovery at room temperature.

Recently there has been progress in the understanding of the mechanism for PWO crystalline matrix damage under proton irradiation [10,11]. Besides the knock-on process, where atoms are displaced from their sites, hadrons can also undergo spallation interactions or induce nuclear fission. Measurements performed with 1 GeV protons

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on ^{208}Pb have shown that the cross-section for spallation interaction is a factor of 10 times larger than it is for fission [12], consequently one can expect that spallation will be dominant in high-energy proton interactions with high Z-nuclei. Early measurements of the products of proton interactions with the heaviest elements [13] support this observation. Spallation interactions are characterized by the creation of light fragments with a large kinetic energy and low-energy heavy recoil nuclei [12,14]. The heavy recoil nuclei lose most of their energy by ionization along their short trajectory, causing little damage to the host. The light fragments, on the other hand, due to their high kinetic energy, propagate through the crystal matrix, creating vacancies, interstitials, and Frenkel Type Defects (FTD) (a vacancy with a neighboring interstitial [7]) along their much longer paths. Since the cross-section for the production of the light fragments is similar for all heavy nuclei, one can expect that the damage mechanism will be similar for crystals with high-Z nuclei and that it will show little dependence on the type of crystal.

In this paper, we report the measurements of the optical transmission damage under proton irradiation of three heavy crystalline materials: PWO, BSO, PbF_2. As these crystals all contain high-Z elements ($Z=82$(Pb) and $Z=83$(Bi)), the contribution of the secondary interaction products to the damage of the crystal matrix can be expected to be the same.

2. Samples and measurements

Three crystal samples were used in these measurements. One was a $2\times2\times1\ cm^3$ PWO crystal produced at the Bogoroditsk Technical Chemical Plant (Russia) in 2008, selected to have a low level of the post-grown-point structure defects, to minimize the γ radiation-induced damage; a $1\times1\times2\ cm^3$ BSO sample manufactured by Shonan Institute of Technology (Japan), and a $2\times2\times10\ cm^3$ PbF_2 crystal, taken from the A4 experiment stock, that was produced by SICCAS (China).

Both BSO and the PbF_2 crystals were irradiated with gammas [6,2] and were allowed to recover over periods of 14 and 13 years, respectively. The PWO crystal was irradiated with gammas from ^{60}Co source to an absorbed dose of 1 kGy followed by a recovery period of 3 months at room temperature.

The three crystals were all exposed to 24 GeV protons in a beam at the CERN Proton Synchrotron (PS) with a flux of 10^9 proton/cm^2/s. The total fluencies were in the range $(3.5-4.2)\times10^{13}$ protons/cm^2, measured with Al foil radiation monitors. During irradiation the crystals were configured with the two small PWO and BSO crystals upstream of the longer PbF_2 crystal. Since the thickness of the PWO and BSO samples is small, approximately 5% of a nuclear interaction length, most of the damage to the three crystals was caused by interactions of the incident protons, rather than by the particles in the cascade of secondary interactions.

The optical transmission spectra of all samples were measured 30 days after the proton irradiation, when the induced radioactivity of the samples had reduced to an acceptable level for handling. A Varian Carry 50 Spectro-Photometer was used for optical transmission measurements. For the PWO and BSO samples, the measurements were made directly in the spectrometer measuring chamber, while a custom-made remote measuring unit, where optical fibers were used to connect the sample to the spectro-photometer, was used for the PbF_2 sample, which had been significantly activated during the irradiation.

The optical transmission spectra of the crystals before and after irradiation with protons are shown in Fig. 1(a)–(c). All the

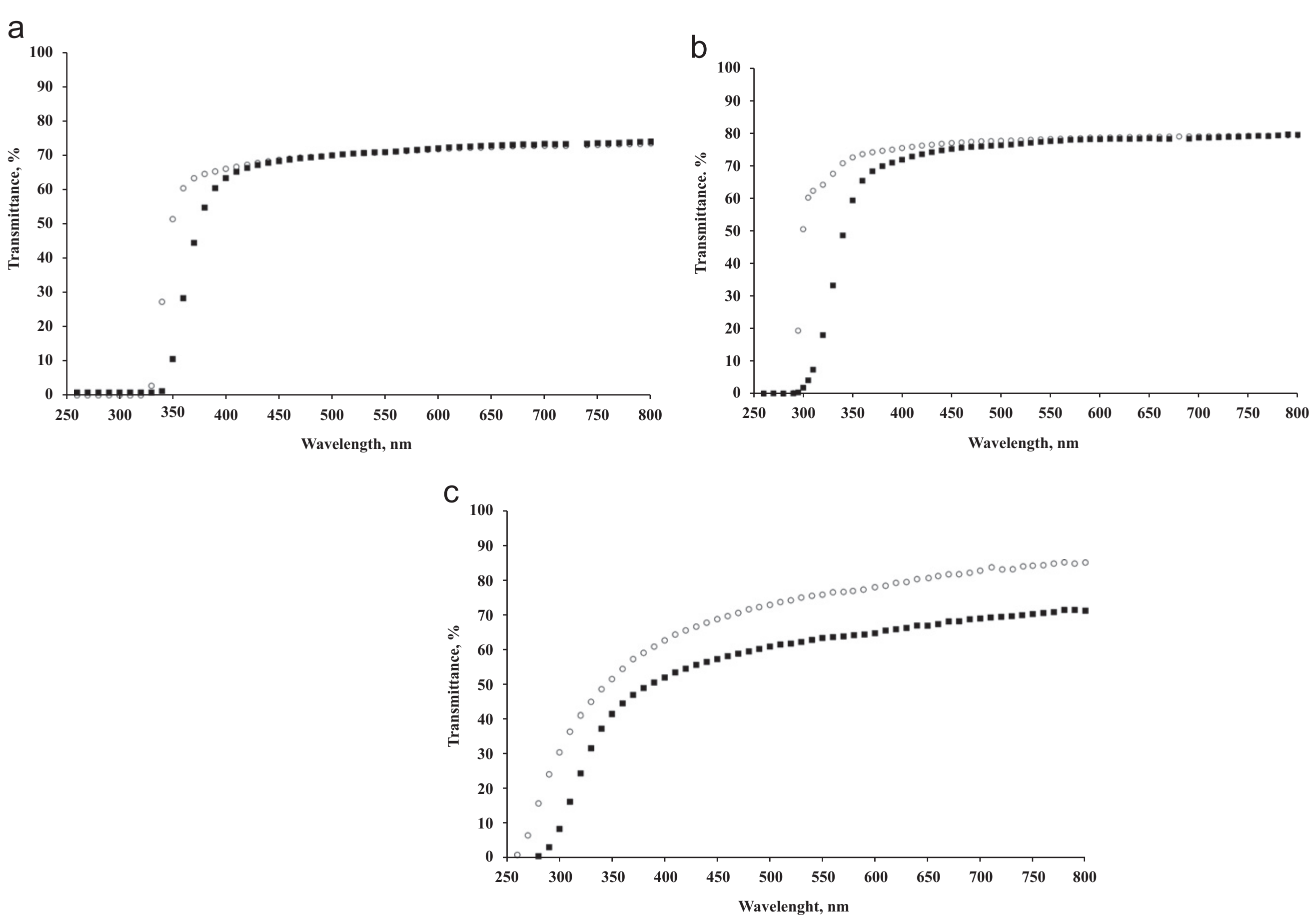

Fig. 1. Transmission spectra of 1 cm long PWO (a), 1 cm long BSO (b) and 10 cm long PbF_2 (c) before irradiation (○) and after irradiation (■) with protons.