Inorganic Scintillators for HEP Calorimetry

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Total absorption electromagnetic calorimeters (ECAL) made of inorganic crystals provide the best energy resolution and detection efficiency for photons and electrons, so are the choice for those HEP experiments requiring the ultimate energy resolution. Novel crystal detectors are being discovered in academic research and in industry, providing an important opportunity for future HEP calorimetry. Supported by the DOE HEP Advanced Detector R&D award and SBIR award, the Caltech HEP crystal laboratory has been actively and successfully carrying R&D on inorganic scintillators for ECAL and time of flight (TOF) detectors in the last several decades. Our effort has been an integrated part of the Caltech HEP program in all frontiers and is actively participated by postdocs and graduate students. We have maintained our unique state of the art facilities and equipment and our partnerships with the National Laboratories and industry partners for test beams and fabrication of novel inorganic scintillators, respectively. Following the DOE basic research needs (BRN) study on HEP Detectors we plan to pursue the following directions. This program is expected to be an integrated part of one of the transversal activities “Materials” of the ECFA DRD collaboration.

- Develop bright, fast and radiation hard inorganic scintillators to face the challenge of the severe radiation environment expected by future HEP experiments at the energy frontier, such as the proposed FCC_{hh}, where up to 5 GGy ionization dose and $5 \times 10^{18} n_{eq}/cm^2$ neutrons are expected. Our irradiation experiments, carried out at CERN, Fermilab, JPL, LANSCE and Sandia, have demonstrated that cerium doped LYSO crystals (LYSO:Ce) survive well up to 4 MGy ionization dose and $10^{16}/cm^2$ for both neutrons and protons. LYSO:Ce+SiPM is now used by the CMS experiment to construct a state-of-the-art barrel timing layer (BTL) system for the HL-LHC. We have also investigated cerium or praseodymium doped garnet, including YAG, LuAG, GGAG, GYAG and GLuAG etc., in both crystal and ceramic form, and found that LuAG:Ce ceramics show a factor of two smaller radiation induced absorption coefficient (RIAC) than LYSO:Ce crystals for both protons and neutrons. Because of more effective use of raw materials and relatively lower processing temperature, materials in a ceramic form are more cost-effective than their crystal counterpart, so are promising for future HEP calorimetry in severe radiation environment. Possible applications of LuAG:Ce ceramics are to replace LYSO:Ce crystal plates as the active material and to use LuAG:Ce ceramic fibers as wavelength shifters for LYSO:Ce crystals in the RADiCAL for a shashlik sampling calorimeter. These bright garnet scintillators, however, suffer from slow scintillation component, which needs to be resolved by e.g., co-doping.

- Develop ultrafast heavy inorganic scintillators with sub-nanosecond decay time to break the ps timing barrier for future TOF system at the energy frontier, and for an ultrafast total absorption ECAL to face the challenge of the unprecedented event rate expected at the intensity frontier, such as Mu2e-II at Fermilab. For a TOF system, the scintillation light in the 1st nanosecond determines the timing resolution, while the slow decay tail causes pileup and readout noise. Inorganic scintillator with core valence transition, such as BaF_2, features with its energy gap between the valence band and the uppermost core band less than the fundamental bandgap, allowing an ultrafast decay time of shorter than 0.5 ns. BaF_2, however, also has a bright slow component with a decay time of about 600 ns. We found that yttrium doping in BaF_2 (BaF_2:Y) suppressed the slow component successfully while maintaining the intensity of the ultrafast component unchanged. In a collaboration with our industrial partner Radiation Monitoring Devices, Inc. (RMD), we also found that Lu_2O_3:Yb ceramics have sub-ns decay time and no slow component. With a very high density of 9.4 g/cm^3, Lu_2O_3:Yb ceramics are promising for future HEP TOF system. Ultrafast inorganic scintillators of this type are expected to offer better timing resolution than the CMS LYSO+SiPM BTL system. Such ultrafast scintillators will also cope with the unprecedented event rate expected by future accelerator-based rare physics searches for lepton flavor violation and low mass dark matter etc. as well as GHz hard X-ray imaging for future free electron laser facilities. R&D will continue to develop ultrafast BaF_2:Y crystals for Mu2e-II and Lu_2O_3:Yb ceramics for future HEP TOF system.

- Develop dense, UV-transparent, and cost-effective inorganic scintillators for the homogeneous hadron calorimeter (HHCAL) detector concept, which is a blue-sky part of the CalVision effort. One of the benchmarks of the CalVision calorimeter for the proposed Higgs factory (ILC or FCC_{ee}) is the ability to discriminate W and Z bosons in their hadronic decay modes. A total absorption calorimeter with all information measured would provide unprecedented jet mass resolution at a level of 20%/√E by using dual readout for either Cerenkov and scintillation light or dual integration gate. Such a longitudinally segmented total absorption calorimeter would also provide a photon pointing capability in addition to excellent energy and position resolutions for electrons, photons and jets. Because of the huge material volume required for such calorimetry, one key issue is to develop cost-effective inorganic crystals of less than a few $ per cc. We have investigated doped PbF_2, PbFCl, BSO and titanium doped sapphire (Al_2O_3:Ti) crystals, as well as ABS, AFO and DSB glasses. With a density of 6 g/cm^3, a radiation length of 1.56 cm, a nuclear absorption length of 24.2 cm and potential low cost of less than 1 $/cc, ABS glass is promising for the HHCAL concept. If successful, cost-effective scintillating glass would introduce a novel calorimeter concept for the proposed Higgs factory.

- Explore other novel ultrafast inorganic scintillators, such as wide gap semiconductor-based crystals with a sub-ns decay time and quantum confinement-based all inorganic $CsPbX_3$, where X = Cl, Br, I, mixed Cl/Br and mixed Br/I, halide perovskite quantum dots. Doped wide-gap semiconductors, such as ZnO:Ga, is known to have bright and fast scintillation light in powder form. Such a material, however, suffers from self-absorption so does not work in bulk. Investigations have been made for such material in nanoparticles embedded in a host. The crucial issue for such a material is density, transmittance and radiation hardness of the host material. Inorganic cesium doped lead halide perovskite was recently found featuring with very bright and tunable emission with sub-ns decay time over visible wavelength. If successful, both materials may also help to break the ps timing barrier for future HEP TOF system.

- Develop compact UV sensitive photodetectors with sufficient dynamic range for ultrafast calorimeters. Recently, we have established a test bench, which can measure quantum efficiency or photon detection efficiency down to 200 nm for PMTs and SiPMs respectively. This test bench has been successfully used for characterization of solar-blind MCP-PMT photodetectors from Photek and SiPMs from FBK. We plan to extend its wavelength coverage down to 170 nm, so that response of photodetectors to scintillation light with wavelength shorter than 200 nm can also be measured. Such a photodetector will also be useful for reading out VUV scintillation light for noble liquid-based detectors.