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CALIFA Barrel prototype detector characterisation

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ABSTRACT

Well established in the field of scintillator detection, Caesium Iodide remains at the forefront of scintillators for use in modern calorimeters. Recent developments in photosensor technology have lead to the production of Large Area Avalanche Photo Diodes (LAAPDs), a huge advancement on traditional photosensors in terms of high internal gain, dynamic range, magnetic field insensitivity, high quantum efficiency and fast recovery time. The R^3B physics programme has a number of requirements for its calorimeter, one of the most challenging being the dual functionality as both a calorimeter and a spectrometer. This involves the simultaneous detection of ~300 MeV protons and gamma rays ranging from 0.1 to 20 MeV. This scintillator – photosensor coupling provides an excellent solution in this capacity, in part due to the near perfect match of the LAAPD quantum efficiency peak to the light output wavelength of CsI(Tl). Modern detector development is guided by use of Monte Carlo simulations to predict detector performance, nonetheless it is essential to benchmark these simulations against real data taken with prototype detector arrays. Here follows an account of the performance of two such prototypes representing different polar regions of the Barrel section of the forthcoming CALIFA calorimeter. Measurements were taken for gamma–ray energies up to 15.1 MeV (Maier-Leibnitz Laboratory, Garching, Germany) and for direct irradiation with a 180 MeV proton beam (The Svedberg Laboratoriet, Uppsala, Sweden). Results are discussed in light of complementary GEANT4 simulations.
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1. Introduction

A powerful technique which has revitalised nuclear physics exploration in recent years is use of inverse kinematics with relativistic, radioactive beams. The fleeting existence of such nuclei at the limits of stability necessitates transportation at the highest possible beam energies. Accordingly, the experimental setup for the Reactions with Relativistic Radioactive Beams, 'R^3B' physics programme must employ a calorimeter at the reaction target which accounts for the relativistic effects of Doppler broadening and shift inherent to a nominal beam energy of 700 A MeV.

This paper is motivated by the development of CALIFA [1], a scintillator based calorimeter to be housed at the future FAIR facility [2]. The calorimeter is divided into two sections, a 'Forward EndCap' covering polar angles between 7° and 43.2° and a cylindrical 'Barrel' section that ensures angular coverage up to 140.3°. The prototypes reported here correspond to different polar regions of the Barrel section.

The ambitious physics programme proposed for the R^3B facility dictates a set of requirements for the intended calorimeter as diverse as they are demanding [3]. This has motivated an extensive research and design campaign to optimise performance in every aspect of the calorimeter, reflected in the design choices taken for the prototypes characterised in this paper. A dedicated simulation campaign undertaken using the R3BRoot analysis framework [4], incorporating GEANT4 [5], has served as an indispensable guide to the development process.

The two prototypes here reported upon, denoted 'Section A' and 'Section B', are of respective geometries relating to different sections of the CALIFA Barrel. The polar region in the calorimeter to which each prototype corresponds is illustrated in Fig. 1.

At the heart of any successful calorimeter are two simple components; the scintillator and the photosensor. Regarding first

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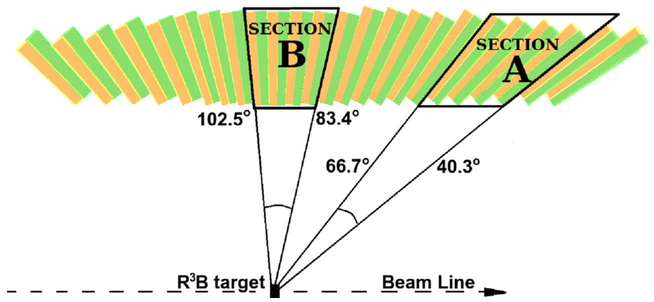

Fig. 1. A visualisation of the Barrel section of the forthcoming CALIFA calorimeter. Different colours denote the crystal type in the chiral pair (two pairs tessellate to fit four crystals to each alveoli). Note the variation of crystal opening angle and length as a function of polar angle. The prototypes correspond to each section as indicated. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

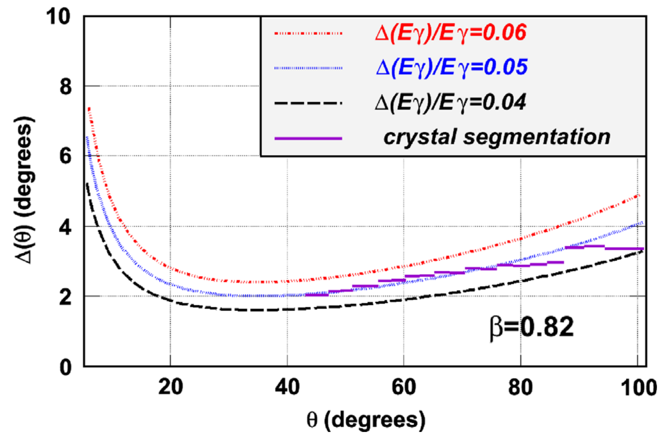

Fig. 2. The geometrical limitation on energy resolution for the R^3B physics programme nominal value of $\beta = 0.82$. CALIFA segmentation is dictated by a 5% minimum, as can be seen by the crystal opening angles overlaid.

the scintillator, for the CALIFA Barrel section CsI(Tl) has been selected. As a scintillation material it offers a number of advantageous properties suited to our purpose: low hygroscopy, high stopping power, high light output in the green-yellow region of the spectrum and good energy resolution [6–8]. However, these positive attributes can be capitalised upon by coupling this established material to recently developed large area avalanche photodiodes, 'LAAPDs'.

Good energy resolution is integral to the performance of a calorimeter and even more crucial for a spectrometer. This combination of scintillator and photosensor is well suited to support such cases as the LAAPD quantum efficiency is not only exceptionally high, but also a near-perfect match to the light output wavelength of CsI(Tl). The combination of these properties is reflected in the good energy resolution measurement of 4.42% at 662 keV achieved via the coupling of a 1 cm^3 CsI(Tl) with a Hamamatsu S12102 LAAPD [9].

A further consideration is the close proximity of the final calorimeter to the forthcoming 4.8 Tm GLAD magnet, the fringe fields of which could distort photosensor operation, PMTs for example requiring shielding. LAAPDs are suitable for use in this environment as they are impervious to magnetic field effects.

One of the most challenging requirements of the R^3B physics programme is the simultaneous measurement of 0.1 MeV gamma rays and proton energies in excess of 300 MeV. Once more the CsI (Tl) – LAAPD combination is outstanding; where most traditional photosensors would struggle with the high photon flux, this combination finds no issues with saturation, enabling detection over a huge dynamic range whilst retaining good energy resolution.

Absorption of high energy protons and gamma-rays requires a greater length of scintillator material. At the R^3B nominal beam energy of 700 A MeV, such emissions observed in the laboratory frame will be increasingly Lorentz boosted in energy with the reduction of the polar angle of emission (θ). Therefore, in the conversion from the laboratory frame to the particle rest frame any uncertainty in θ imposes a geometrical limitation on the energy resolution. This Doppler broadening is in turn dependent on the polar angle itself. These requirements dictate the detector segmentation and length across the polar range of the calorimeter. The angular dependence is illustrated for different energy resolution values in Fig. 2, further details of which can be found in Ref. [10]. Here θ refers to the polar angle from the beam line at the R^3B target, while $\Delta(\theta)$ represents the angular uncertainty on the polar angle. The crystal segmentation is shown also, corresponding to the 5% at 1 MeV energy resolution requirement of the R^3B physics programme [3].

As seen in Fig. 2 the geometrical limitation on energy resolution can be improved by increasing detector segmentation. However, the inclusion of further passive material decreases calorimeter efficiency and promotes the fraction of protons traversing between scintillator elements. In any case, the intrinsic energy resolution of CsI(Tl) limits the improvement from further segmentation to much below 5% at 1 MeV. Other scintillators are available with superior intrinsic energy resolution, though these tend to be highly hygroscopic – the additional encapsulation required degrading the summed energy signal for inter-crystal scattered protons. The CsI(Tl) granularity has been optimised in such a manner as to ensure that the final resolution is not dominated by Doppler broadening, but close to the intrinsic resolution of the scintillation material, within the R^3B energy resolution requirements.

The two experiments here addressed regard the detection of high energy gamma rays at the Maier-Leibnitz Laboratory, Garching, Germany (MLL), and the measurement of high energy protons at The Svedberg Laboratoriet, Uppsala, Sweden (TSL), respectively. Each set of experimental data serves both as a validation of the GEANT4 simulations and an investigation into the response of different calorimetric sections under realistic experimental conditions.

2. High energy gamma rays, MLL

2.1. Experimental overview

Under investigation at the Maier-Leibnitz Laboratory, Garching, was a prototype detector which corresponded to the forward orientated 'Section A' of the CALIFA Barrel [1]. The MLL tandem accelerator was used to impinge 24 MeV protons onto a 12 mm carbon target. The resulting target excitation includes a significant population of the 2_1^+ and 1_2^+ excited states, which decay via the emission of gamma rays of 4.4 and 15.1 MeV, respectively. The detector was positioned at a polar angle of 37° from the beam, at a distance of 290 mm from the target. Aluminium shielding of a 4 mm thickness was employed to remove the elastic and inelastic scattered protons incident on the detector, as seen in Fig. 3.

2.2. Section A prototype

The Section A prototype consists of 16 CsI(Tl) truncated pyramidal crystals[1] in a 4×4 array, each crystal with an opening face of 12.2×23.2 mm, tapered to an exit face of 17×32 mm along a length of 180 mm. The exit face dimensions are well matched to the Hamamatsu S12102 'double' LAAPDs employed, which consist of

[1] Supplied by Amcrys Ltd.

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