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Construction and performance of the barrel electromagnetic calorimeter for the GlueX experiment

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A B S T R A C T

The barrel calorimeter is part of the new spectrometer installed in Hall D at Jefferson Lab for the GlueX experiment. The calorimeter was installed in 2013, commissioned in 2014 and has been operating routinely since early 2015. The detector configuration, associated Monte Carlo simulations, calibration and operational performance are described herein. The calorimeter records the time and energy deposited by charged and neutral particles created by a multi-GeV photon beam. It is constructed as a lead and scintillating-fiber calorimeter and read out with 3840 large-area silicon photomultiplier arrays. Particles impinge on the detector over a wide range of angles, from normal incidence at 90 degrees down to 11.5 degrees, which defines a geometry that is fairly unique among calorimeters. The response of the calorimeter has been measured during a running experiment and performs as expected for electromagnetic showers below 2.5 GeV. We characterize the performance of the BCAL using the energy resolution integrated over typical angular distributions for π^0 and η production of $\sigma_E/E = 5.2\%/\sqrt{E(\mathrm{GeV})} \oplus 3.6\%$ and a timing resolution of $\sigma = 150$ ps at 1 GeV.

1. GlueX detector

The primary motivation of the GlueX experiment is to search for and, ultimately, study the pattern of gluonic excitations in the meson spectra produced in γp collisions at 9 GeV [1]. Specifically, GlueX aims to study the properties of hybrid mesons — particles where the gluonic field contributes directly to the J^{PC} quantum numbers of the mesons [2]. The design of the GlueX detector [3] is based on a solenoidal magnet that surrounds all detectors in the central region, providing a magnetic field of about 2 T along the direction of the photon beam, which impinges on a 30 cm-long liquid hydrogen target. A schematic of the detector including its major sub-detectors is given in Fig. 1. The goal of GlueX calorimetry is to detect and to measure photons from the decays of π^0's and η's and other radiative decays of secondary hadrons. The detector measures the energies and positions of the showers made by photons, as well as the timing of the hits. It also provides the timing of the hits caused by charged hadrons, allowing for time-of-flight particle identification.

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2. BCAL: overview and design

A practical solution to the requirements and constraints imposed by the experiment is a calorimeter based on lead-scintillating fiber sandwich technology. The BCAL is modeled closely after the electromagnetic calorimeter built for the KLOE experiment at DAΦNE [8–10]. The BCAL detects photon showers with energies between 0.05 GeV and several GeV, 11°–126° in polar angle, and 0°–360° in azimuthal angle. The containment of showers depends on the angle of particle incidence, with a thickness of 15.3 radiation lengths for particles entering normal to the calorimeter face and reaching up to 67 radiation lengths at 14°. Geometrically, the BCAL consists of 48 optically isolated modules each with a trapezoidal cross section, forming a 390 cm-long cylindrical shell having inner and outer radii of 65 cm and 90 cm, respectively. The fibers run parallel to the cylindrical axis of the detector. Schematics showing the geometry of the BCAL and readout segmentation are included in Fig. 2.

The light is collected via small light guides at each end of the module and is delivered to silicon photomultiplier (SiPM) light detectors, which were chosen due to their insensitivity to magnetic fields. Preamplifiers and summing circuits are situated near the light sensors and generate signals that are delivered to VXS electronics racks, conveniently located on the floor of the experimental hall.

The performance of the calorimeter is summarized by its ability to measure the energy, position and timing of electromagnetic showers. In general, the energy resolution of an electromagnetic calorimeter is expressed in the form:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E(\mathrm{GeV})}} \oplus b \oplus \frac{c'}{E(\mathrm{GeV})}, \qquad (1)$$

where the symbol $\oplus$ means that the quantities are added in quadrature. The $a/\sqrt{E}$ term contains the combined effect of sampling fluctuations and photoelectron statistics, with the former dominating the resolution. This is commonly referred to as the stochastic term. The constant term, b in Eq. (1), originates from sources with uncertainties that scale with energy. These sources can be mechanical imperfections, material defects, segment-to-segment calibration variations, instability with time and shower leakage. The term c'/E results from noise and pileup in high-rate environments. Measurements of an early full-length prototype[3] using a photon beam [11] provided expectations for the various contributions to the resolution: $a \approx 5.4\%\sqrt{\mathrm{GeV}}$, $b \approx 2.3\%$ and c' negligible.

The azimuthal angular resolution is dominated by the readout granularity in azimuth, which is about 2 cm. The polar angular resolution depends on the position resolution along the length of the barrel (z), which is determined by measuring the time difference between signal arrivals at the upstream and downstream faces of the barrel. The resolution in z depends on the resolution of half the time difference, which may be parameterized as

$$\sigma_t = \frac{c}{\sqrt{E(\mathrm{GeV})}} + d, \qquad (2)$$

where c and d are empirical constants. At 1 GeV, the prototypes obtained a timing resolution of $\sigma_t \approx 200$ ps, which leads to a resolution in z of $\sigma_z \approx 3$ cm. The timing resolution is also important for measuring flight times from the target, which are used to help with charged particle identification.

In the following sections we provide details of the individual components that were used in the construction of the BCAL and then describe the performance of the calorimeter during the experiment.

[3] The matrix material of the prototype was very similar to the final detector. However, the readout used standard photomultiplier tubes and a uniform segmentation, which could result in a different energy dependence for the resolution.

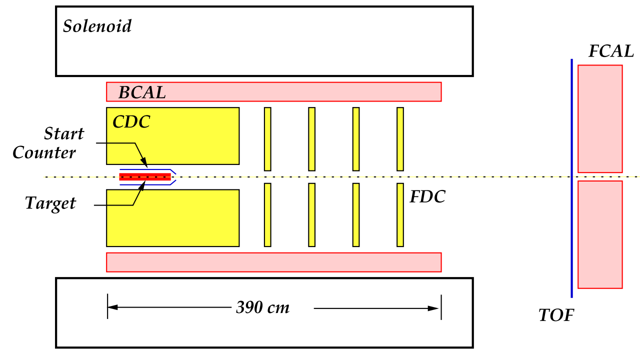

Fig. 1. Sketch of GlueX detector. The main systems of the detector are the Start Counter [4], the Central Drift Chamber (CDC) [5] the Forward Drift Chamber (FDC) [6], a scintillator-based Time of Flight (TOF) wall and a lead-glass Forward Calorimeter (FCAL) [7]. The Barrel Calorimeter (BCAL) is sandwiched between the drift chambers and the inner radius of the solenoid. (Color online).

3. Major components

3.1. Fiber selection

Kuraray SCSF-78MJ double-clad, blue–green fibers[4] [12] were selected for their high light output and long attenuation length (∼4 m). The light yield affects the energy and timing resolutions as well as the detection threshold. Over three quarters of a million fibers were used in the construction of the BCAL. Fiber testing and the fabrication of the BCAL modules were carried out at the University of Regina. Acceptance testing of the fibers was based on measuring the response of about 0.5% of the fibers, which were selected uniformly from each of the manufactured batches. These fibers were evaluated by employing a 373-nm UV LED to stimulate the fibers along their length and reading out the light using a spectrophotometer and a photodiode in order to extract the spectral response and the attenuation length, respectively [13]. Single exponential fits to the spectral response at 100–280 cm distance from the light source yielded an average bulk attenuation length and standard deviation of (387 ± 26) cm. Double-exponential fits to the spectral response over the entire 4-m length also allowed the extraction of long and short attenuation-length components at (486 ± 54) cm and (75 ± 22) cm, respectively. The relative strength of the short to long attenuation lengths was determined to be 0.3 ± 0.08.

The quality of these fibers was evaluated further by exciting the fibers at their mid point using a ^{90}Sr source in order to determine the light yield using a calibrated photomultiplier (PMT)[5] attached to one end of the tested fiber. The average number of photoelectrons from this sample was 9.2 ± 0.6 at a source distance of 200 cm from the PMT [14,15].

3.2. Matrix construction

Each BCAL module consists of 185 layers of corrugated lead sheets that are 0.5 mm thick. They are interleaved with 184 layers of 1-mm fibers bonded to the 0.5-mm grooves in the lead sheets using BC-600 optical cement.[6] During construction, the overhead fluorescent lights were covered with yellow UV-absorbing film (TA-81-XSR[7]) to protect the fibers from UV exposure [13]. Custom devices were built for the

[4] Kuraray Plastic Scintillating Fibers (http://www.kuraray.com/products/plastic/psf.html).
[5] Hamamatsu R329-02 with a standard progressive voltage divider.
[6] St. Gobain Crystals & Detectors, Hiram, OH 44234, USA (http://www.bicron.com).
[7] Window Film Systems, London, ON, Canada (https://www.windowfilmsystems.com).