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Design and performance of a lead fluoride detector as a luminosity monitor

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ABSTRACT

Precise luminosity measurements for the OLYMPUS two-photon exchange experiment at DESY were performed by counting scattering events with alternating beams of electrons and positrons incident on atomic electrons in a gaseous hydrogen target. Final products of Møller, Bhabha, and pair annihilation interactions were observed using a pair of lead fluoride Cherenkov calorimeters with custom housings and electronics, adapted from a system used by the A4 parity violation experiment at MAMI. This paper describes the design, calibration, and operation of these detectors. An explanation of the Monte Carlo methods used to simulate the physical processes involved both at the scattering vertices and in the detector apparatus is also included.

1. Introduction

1.1. Purpose

A significant discrepancy persists between the results of two classes of experiments that have measured the ratio of proton form factors, G_E/G_M [1]. The gap between data from polarization-transfer experiments and those from analyses using Rosenbluth separation could be due in part to contributions from two-photon exchange. Observable effects of this proposed explanation have been modeled in various ways [2] and a precise measurement is needed to test the validity of published theories. The OLYMPUS experiment [3] aims to quantify two-photon exchange over a range of four-momentum transfer of $0.4\ \mathrm{GeV}^2/c^2 < Q^2 < 2.2\ \mathrm{GeV}^2/c^2$ through a measurement of the ratio of electron–proton to positron–proton elastic scattering cross sections with a total uncertainty of less than 1%.

Installed at the DORIS storage ring at DESY, OLYMPUS collected data with a circulated 2.01 GeV lepton beam, alternating about daily between electrons and positrons, incident on a gaseous hydrogen target. Kinematics were overconstrained by coincident detection of the scattered lepton and the recoiling proton in a large-acceptance spectrometer inheriting from that used in the BLAST experiment at MIT-Bates [4]. Crucial to achieving the desired accuracy of the results is a precise measurement of the luminosity. While precision on an absolute scale is always desirable, for a result that relies on a ratio it is the precision of the relative luminosity measurement between beam species that is of prime concern.

To this end, multiple subsystems were used to make complementary luminosity determinations based on distinct physical signals. First, slow control software provided a quick estimate based on the temperature of the target cell, the flow rate of hydrogen into the cell, and the beam current. Second, small-acceptance tracking detectors at polar scattering angles of about 12° were used to count events in that region, where the lepton–proton elastic scattering cross-section is higher than in the spectrometer and where two-photon exchange effects are expected to be negligible [2]. Finally, interactions between the beam and atomic electrons in the target were monitored with a pair of Cherenkov calorimeters placed about 3 m downstream of the target center at the symmetric Møller scattering angle, that is, the polar scattering angle in the lab frame common to both outgoing electrons when they have the same energy. For a beam energy of 2.01 GeV incident on a stationary target, this is 1.29°.

This paper describes the design and operation of these “Symmetric Møller/Bhabha” (SYMB) calorimeters. They were built to handle an accepted rate of $e^{\pm}$–e^{-} interactions (with products detected in coincidence) of typically 5 kHz. The choice of detector

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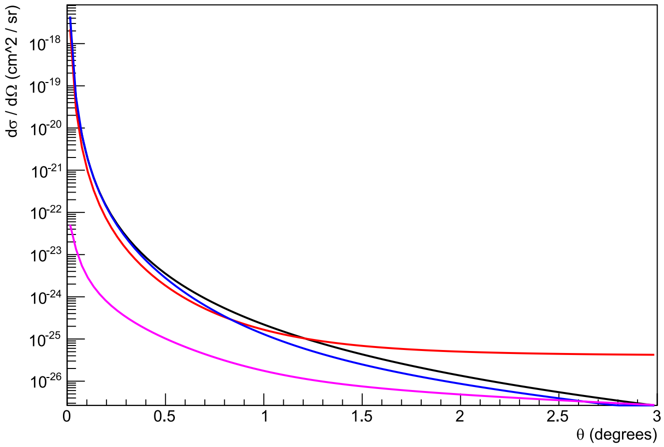

Fig. 1. Elastic cross sections as a function of lab-frame scattering angle: Møller scattering (red), Bhabha scattering (blue), pair annihilation (violet), and electron-proton scattering (black). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

material needed to be sufficiently radiation hard to maintain consistent performance levels while absorbing a significant dose of high-energy particles and able to provide a fast physical response allowing for signal collection at a kilohertz rate. These considerations led to the use of PbF_2 crystals, in which energetic charged particles produce Cherenkov light with no scintillation component. Photomultiplier tubes (PMTs) gathered the light from each detector. Their output was passed through analog-to-digital converters (ADCs) and recorded on 8-bit by 8-bit two-dimensional histogramming cards.

1.2. Theoretical considerations

Three elastic processes contributed to the observed physical signal: Møller scattering ($e^-e^- \to e^-e^-$), Bhabha scattering ($e^+e^- \to e^+e^-$), and pair annihilation ($e^+e^- \to \gamma\gamma$). All three are pure quantum electrodynamic processes whose cross sections are depicted around the region of interest in Fig. 1 along with the electron–proton scattering cross section in the Born approximation (where it is equivalent to the positron–proton scattering cross section) for reference. Next-to-leading order corrections [5], including corrections due to radiative final states, were accounted for in the analysis by means of Monte Carlo simulation. The simple nature of these quantum interactions, along with the high acceptance-integrated cross-sections relative to those of elastic $e^\pm$–p scattering, provided an opportunity for very precise luminosity measurements at OLYMPUS.

2. Design

Two identical SYMB detectors were built in Mainz, one for each “sector” of OLYMPUS (the left and right sides, from the beam's perspective). Each detector consisted of a 3×3 array of lead fluoride (PbF_2) crystals placed inside a mu-metal box along with a PMT for each crystal and voltage dividers. Just outside the box, on the side facing the target, a lead (Pb) collimator was installed. All components were fastened to a support table so that they could be moved away from the beam line in a controlled way in order to avoid radiation damage during DORIS injections. They could then be precisely returned back to their original positions. In practice, injections were well controlled and this functionality was not needed during normal operation. A schematic of the SYMB detector, target, and beam pipe is presented in Fig. 2 to provide a sense of scale.

2.1. PbF_2 crystals

All crystals used in the detectors were provided by the A4 collaboration at MAMI in Mainz [6]. Note that these were not regenerated crystals previously used by A4, but “brand new” unused crystals. The lengths of the crystals varied from 150.0 mm to 185.4 mm, each tapered slightly from its front (upstream) face to its back (downstream) face. These faces were trapezoids, with an area of ~670 mm^2 for the front and ~900 mm^2 for the back. Given PbF_2's radiation length of 9.34 mm and Molière radius of 21.24 mm [7], such dimensions are sufficient for a 3×3 array to contain more than 95% of the energy of an electromagnetic cascade [8].

OLYMPUS was designed with an integrated luminosity goal of 4 fb^{-1}. Integrating over the region allowed by the collimator aperture, the accepted cross section was expected to be less than 50 nb for each SYMB process. With less than 1 GeV deposited in each central crystal per event, and given the size and density of the crystals, the total absorbed dose due to signal events over the course of the experiment was estimated to be no greater than 25 Gy. Allowing for some additional ionizing radiation from other sources, this was still considered safe, as even 100 Gy would be likely to cause only minor damage to the transmittance of the crystals [9].

Since PbF_2 is a pure Cherenkov material with no slow component in its light output, it has a fast rise time of ~5 ns and the full pulse width is well contained within a 20 ns window. (This was a useful feature for gating signals, since the DORIS beam structure consisted of lepton bunches 24 ps wide and about 100 ns apart.) Each crystal was wrapped with Millipore paper (Immobilon-P) to improve internal reflection at the faces, then glued to a PMT (Philips XP2900/01). The custom-made PMT bases were actively stabilized to handle particle rates up to several MHz without any change in gain [10]. The completed arrays were tightly bound together by foil and tape.

2.2. Collimator

Beam halo and bremsstrahlung prompted the use of a Pb block collimator shielding the front of each detector. The collimator's

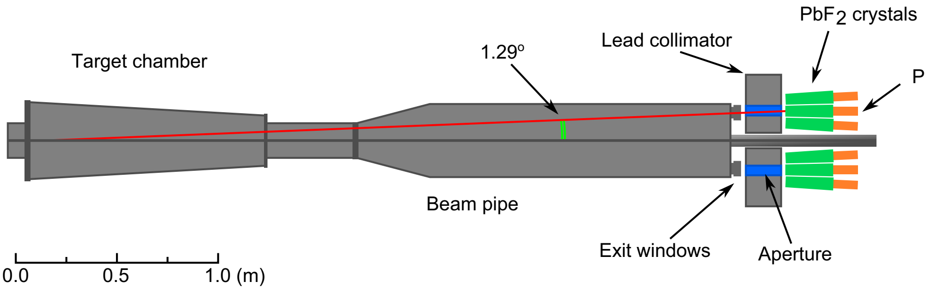

Fig. 2. A scale representation of the critical elements. The support table and other electronics are omitted for clarity and other OLYMPUS detector systems are not drawn.