Nuclear Inst. and Methods in Physics Research, A 896 (2018) 96–102

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Study of light backgrounds from relativistic electrons in air light-guides

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A R T I C L E I N F O

Keywords:
MOLLER project
Beam test
Gas scintillation
Cherenkov
Geant4 simulation

A B S T R A C T

The MOLLER experiment proposed at the Thomas Jefferson National Accelerator Facility plans a precision low energy determination of the weak mixing angle via the measurement of the parity-violating asymmetry in the scattering of high energy longitudinally polarized electrons from electrons bound in a liquid hydrogen target (Møller scattering). A relative measure of the scattering rate is planned to be obtained by intercepting the Møller scattered electrons with a circular array of thin fused silica tiles attached to air light guides, which facilitate the transport of Cherenkov photons generated within the tiles to photomultiplier tubes (PMTs). The scattered flux will also pass through the light guides of downstream tiles, generating additional Cherenkov as well as scintillation light and is a potential background. In order to estimate the rate of these backgrounds, a gas-filled tube detector was designed and deployed in an electron beam at the MAMI facility at Johannes Gutenberg University, Mainz, Germany. Described in this paper is the design of a detector to measure separately the scintillation and Cherenkov responses of gas mixtures from relativistic electrons, the results of studies of several gas mixtures with comparisons to simulations, and conclusions about the implications for the design of the MOLLER detector apparatus.

1. Introduction

The next generation of precision tests of the Standard Model at modern accelerator facilities requires the use of large area, open geometry detectors to obtain the required statistical precision, which in turn necessitates novel detector configurations and experimental techniques. The MOLLER experiment [1–3] intends to study a parity-violating signal in the Møller scattering process to measure the weak mixing angle $\sin^2\theta_W$ at the Thomas Jefferson National Accelerator Facility. It will utilize several concentric rings of fused silica Cherenkov radiators as the primary detectors for the scattered electrons. Such an arrangement allows for in principle the total azimuthal coverage of the Møller scattering process, but due to the large acceptance one must carefully account for a number sources of background, including those from the primary flux itself.

Shown in Fig. 1, the overall experimental design calls for an 11 GeV polarized electron beam to impinge on a 1.5 m liquid hydrogen target with a spectrometer and collimator system designed to collect Møller scattered electrons in the full range of the azimuth, and a center-of-mass polar angle range of 60° to 120°. This corresponds to laboratory scattering angles of 5 to 20 mrad. A 1π-collimation system with an odd number of apertures symmetric in center-of-mass polar angle is designed to detect one of the pair of indistinguishable electrons in the Møller scattering process, hence offering 2π azimuthal coverage as both electrons are in the same scattering plane. Two toroidal magnetic elements will transport particles from various scattering processes downstream into a set of concentric annuli; azimuthal-defocussing in the spectrometer

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https://doi.org/10.1016/j.nima.2018.04.029
Received 19 October 2017; Received in revised form 15 April 2018; Accepted 15 April 2018
Available online 22 April 2018
0168-9002/

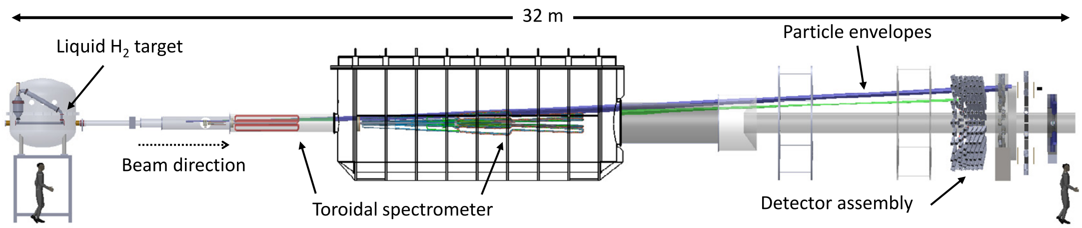

Fig. 1. A schematic of the MOLLER experiment setup.

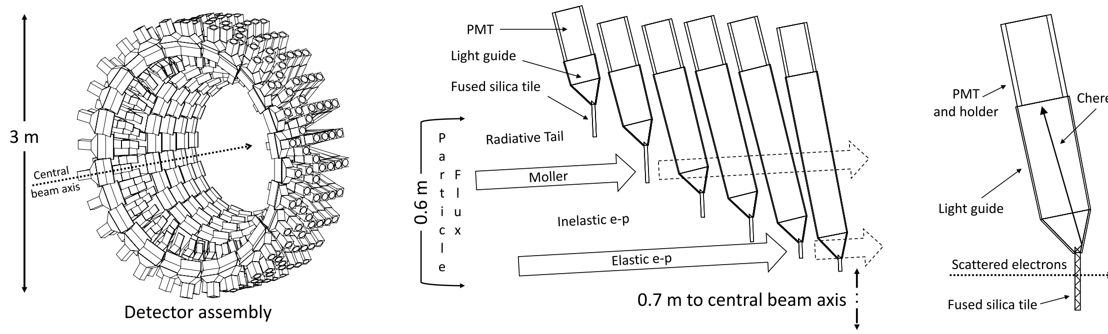

Fig. 2. A schematic of the MOLLER experiment detector design. The full array is shown left. The different signals are focused into separate radial regions (center) and pass through the light guides of the following rings. A charged particle passing through the fused silica tile while generating Cherenkov photons is illustrated in the right plot.

produces a scattered flux distribution at the detector plane in the full range of the azimuth 30 m downstream of the target.

Fig. 2 (left) shows a schematic perspective view of the azimuthally and radially segmented detector array designed to intercept the electron annuli. Looking downstream along the beam axis, the fused silica tiles form a series of concentric rings. Each annulus will intersect electrons in different combinations scattering processes, such as Møller scattering, elastic electron–proton scattering, and inelastic electron–proton scattering. Coherent and incoherent photon radiation will additionally cause the migration of electrons into other detector regions.

Fig. 2 (right) shows a diagram of how each tile is coupled to a long air light guide to channel tile-produced Cherenkov light to a PMT. Fig. 2 (center) shows a cross-sectional view of the tile, light guide, and PMT arrangement. The rings are ordered such that larger radii are further upstream. Particles will therefore pass through their respective tile and subsequently all light guides belonging to smaller radius tiles. This allows for the possibility that Cherenkov or scintillation light generated in the light guide volume will add to the signal from the tiles. While the Cherenkov light yield, energy, and direction are readily calculable given an index of refraction, the detailed scintillation yield properties of gases are less well-known. Scintillation can also be a dominant contribution as it has an isotropic distribution and more difficult to geometrically suppress.

A previous forward angle kaon experimental proposal known as KOPIO faced a similar problem and carried out a systematic analysis of scintillation yield in various gas mixtures [4]. Their results suggest that the potential background in the MOLLER design with a PMT of a similar response would be small, of order of 0.2% in the main Møller rings, and could be as large as 10%–20% in other rings. Such a background would dilute the parity-violating asymmetry and reduce the effective analyzing power in various rings.

For a more accurate estimate of the background, a measurement was performed of the light yield from high energy electrons traversing various gases using a PMT with a similar wavelength response to those planned for use in the MOLLER experiment. Aside from air, the possibility of specialized gas mixtures was also explored. In the following a description of the measurement apparatus and experimental configurations is provided. An analysis of the collected data, a comparison to simulation, and our conclusions as applied to the MOLLER apparatus are also presented.

2. Scintillation test

2.1. Detector design

To measure the Cherenkov and scintillation yields, a detector was constructed which consists of a tube filled with gas whose axis is collinear with an incident electron beam, as shown in Fig. 3. Anolux UVS mirrors angled 45° to the axis are placed on each end which serve to reflect generated light into a PMT which lies 90° to the axis. The test was carried out using two Hamamatsu H3177 PMTs. The quantum efficiency as a function of wavelength provided by the manufacturer is shown in Fig. 4. The reflectivity of the mirror, as shown in Fig. 5, was measured at an incident angle of 45° for photons over a range of optical and ultraviolet wavelengths. The upstream PMT will predominantly detect isotropically-produced scintillation light and the downstream PMT will detect both scintillation light and Cherenkov light. In practice, reflections from the downstream PMT will propagate some Cherenkov signal to the upstream PMT and is accounted for by collecting data with the downstream PMT and mirror removed and the aperture sealed with a non-reflective surface. The calculable Cherenkov signal serves as a known reference quantity.

The inner diameter of the tube was about 2 in, which is slightly larger than the chosen PMT radius. The amount of collected scintillation light is a combination of length of the detector and the inverse radius-squared distance from where the light is produced. An interaction length of about 23.5 in was chosen so that the largest Cherenkov ring (produced by the most upstream electrons) would match the size of the PMT photocathode.

The integrated Cherenkov production per unit energy per electron can be approximated by

$$\frac{d^2N}{dEdx} \approx 370\ \sin^2\theta_c\ \mathrm{eV}^{-1}\mathrm{cm}^{-1} \tag{1}$$