A Cosmic Ray Muon Spectrometer Using Pressurized Gaseous Cherenkov Radiators

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Abstract—In this work, we propose a new approach to cosmic ray muon momentum measurement using multiple pressurized gaseous Cherenkov radiators. Knowledge of cosmic ray muon momentum spectrum has the potential to significantly improve and expand the use of a variety of recently developed muon-based radiographic techniques. However, existing muon tomography systems rely only on muon tracking and have no momentum measurement capabilities which reduces the image resolution and requires longer measurement times. A fieldable cosmic ray muon spectrometer with momentum measurement capabilities for use in muon tomography is currently missing. We address this challenge by optimally varying the pressure of multiple gaseous Cherenkov radiators and identifying the radiators that are triggered by muons that have momentum higher than the Cherenkov threshold momentum. We evaluate the proposed concept through Monte Carlo simulations and demonstrate that the sea level cosmic ray muon momentum spectrum can be reconstructed with sufficient accuracy and resolution for two scenarios: (i) a perfect Cherenkov radiator and (ii) a practical Cherenkov radiator where noise was introduced in the form of scintillation and transition photons. To quantify the detector classification accuracy, true and false classifications are introduced. The fraction of true classification is investigated for each momentum level in a practical radiator. The average classification rate for momenta 0.2 to 7.0 GeV/c with uncertainty 1 GeV/c was higher than 85%.

Index Terms—Cosmic ray muons, Muon momentum measurement, Muon spectrometers, Cherenkov radiation.

I. INTRODUCTION

COSMIC ray muon radiography, is a promising non-destructive technique that is often utilized to monitor or image the contents of dense or well shielded objects, typically not feasible with conventional radiography techniques. Muography has been used with various levels of success in spent nuclear fuel monitoring [1] and cargo container imaging [2]. However, in practice, muography suffers from long measurement times limiting its widespread applicability. Although the benefits of measuring muon momentum coupled with existing tomography systems have been discussed [3], it is still very challenging to deploy existing muon spectrometers in the field due to size and cost limitations. Even though recent efforts [4-5] to develop a muon spectrometer for use in muon scattering tomography show promise, a portable prototype has yet to be developed. In this work, we present a concept for measuring muon momentum using multiple gaseous Cherenkov radiators. By varying the pressure of multiple gas Cherenkov radiators, a set of muon momentum threshold levels can be selected that are triggered only when the incoming muon momentum exceeds that level. As a result, depending on the incoming muon momentum, none to all Cherenkov radiators can be triggered. By analyzing the signals from each radiator, we can estimate the actual muon momentum. The primary benefits of such a concept is that is can be compact and portable enough so that it can be developed in the filed separately or in combination with existing muon tomography systems.

II. MUON MOMENTUM MEASUREMENT USING CHERENKOV RADIATION

When a muon travels through a transparent medium at a speed greater than the speed of light in that medium, Cherenkov radiation is emitted. The threshold muon momentum, \( p_{th} \), needed to induce Cherenkov radiation is:

\[
p_{th} = \frac{m_{\mu} c^2}{\sqrt{n^2 - 1}}
\]

where \( n \) is the refractive index, \( m_{\mu} \) is the muon mass, and \( c \) is the speed of light. For gaseous media, the refractive index is a function of pressure and temperature and it can be estimated using the Lorentz-Lorenz equation:

\[
n \approx \sqrt{1 + \frac{3A p}{RT}}
\]

where \( A \) is the molecular refractivity in \( m^3/mol \), \( R \) is the universal gas constant, \( p \) is pressure and \( T \) is temperature. From (2), the refractive index can be varied by pressurizing a gaseous radiator at a constant temperature. The conceptual design of the proposed spectrometer is shown in Fig. 1. Each numbered box represents a gas radiator with various muon momentum threshold levels. Assuming that a muon with an energy of 3.1 GeV passes through all the pressurized gas radiators, radiators are triggered up to \#5 (>3.0 GeV/c). The amplitude of expected Cherenkov photon signals decreases because the refractive indices become smaller for higher threshold momentum levels. Taking off difference of adjacent binary signals, the true momentum range can be identified.
III. RESULTS

To evaluate and validate the proposed spectrometer, we performed detailed Monte Carlo simulations using MATLAB. The cosmic muon momentum spectrum at sea level was simulated using a Monte Carlo Muon generator [6]. We then categorized the incoming muon momentum into seven momentum levels from 0.2 to 7.0 GeV/c with an interval of 1.0 GeV/c. In a perfect radiator, signals are only generated by Cherenkov photons. In a practical radiator, however, Cherenkov, scintillation and transition photons are also simulated. The characteristic photon emissions by Cherenkov, scintillation, and transition in radiator A \( (p_\mu > p_{th}) \) and radiator B \( (p_\mu < p_{th}) \). are shown in Fig. 2. The simulation results are shown in Fig. 3 including the (i) actual sea level muon momentum spectrum, (ii) reproduced muon momentum spectrum by a perfect pressurized gas Cherenkov radiator and, (iii) a practical radiator. Our muon spectrometer successfully classifies the incoming muon momenta and correctly reproduces the sea level muon spectrum. The measurement results are also classified into two classification levels, true classification and false classification. The results of the classification rate are presented in Fig. 3-(c).

IV. CONCLUSION

Knowledge of the cosmic muon momentum can play a significant role in muon scattering tomography. In this paper, we propose a new concept for muon momentum measurement using pressurized gaseous Cherenkov radiators. We showed that the use of multiple pressurized gas Cherenkov radiators has the potential to successfully measure the incoming cosmic muon momentum with a measurement resolution of 1.0 GeV/c within the range between 0.2 and 7.0 GeV/c. To verify the classification accuracy, muon spectrum was reconstructed in MATLAB for two scenarios. In both scenarios the reconstructed spectrum was in good agreement with the measured cosmic ray muon spectrum and the momentum classification rate was above 85%.

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