Feasibility study of magnetic field measurement system using cosmic-ray muons

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（宇宙線ミュオンを用いた磁場測定システムの実用性に関する研究）

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論 文 内 容 の 要 旨

Thesis Summary

Over a hundred years ago, Victor Hess's groundbreaking discovery of cosmic rays marked a new era in the field of particle physics. One of the most remarkable advancements in this field is the use of cosmic-ray muons. These particles, showering the Earth's surface at a rate of roughly 10,000 per square meter per minute, have been deployed for a variety of applications. Their unique properties, including the ability to penetrate deeply into any material, their universal availability (even underground), nearly perfect detection efficiency, and non-destructive interaction with objects, make them invaluable. One notable technique that leverages these properties is muon radiography, also known as muography. This technique primarily serves two major purposes: it enables the survey of the internal structure of large objects through the absorption ratio and facilitates the inspection of hidden nuclear materials based on scattering angle.

This technology was initially employed by Alvarez for the purpose of exploring hidden chambers within the pyramids. Despite the initial promise and potential of this technology, there was a period of prolonged inactivity, largely due to the technological demands of muography detectors which limited its widespread applications. Nevertheless, with the recent breakthroughs in detector technology such as large-scale data acquisition system, commercial detector availability, and data analysis technology made many researchers possible to apply muography for various targets. The application of muography has expanded to areas such as volcanology, geotomography, nuclear waste investigations, nuclear reactor inspections, detection of high-Z materials, imaging of cultural heritage artifacts, and even assessing infrastructure degradation.

Magnetic fields are one of the principal forces in nature, playing an instrumental role in a multitude of natural phenomena and technological applications, including but not limited to accelerators, medical imaging, electric cars, and fusion reactors. However, existing methods for accurately measuring and monitoring magnetic fields are not without limitations. Traditional magnetic field detection techniques, such as Hall effect sensors and loop coils, although useful in providing valuable data on local magnetic fields, often lack for measuring large targets and they must touch the magnetic field to provide us the information of the magnet and inserting the probe will cause some difficulties. As a result, there is an increasing effort to improve magnetic field detection and characterization.

Muon particles are fundamentally elementary particles similar to electrons, but much heavier. They carry an electric charge identical in magnitude to that of an electron, and we find both positive and negative muons. This characteristic is crucial when discussing their behavior in magnetic fields. Due to their charged nature, muons are subject to the Lorentz force when moving through a magnetic field, which can deflect their trajectory. Notably, this deflection is not random;

instead, it follows a helical path as dictated by the right-hand rule. The degree of deflection is influenced by several factors, including the muon's velocity, charge, and the strength of the magnetic field. This study explores the feasibility of using cosmic-ray muons, given their natural abundance, unique characteristics, and behavior in magnetic fields, as potential tools for magnetic field measurement. Simultaneously, the effect of magnetic fields –0on muography images and material identification is significant, yet there are no studies addressing the interference of magnetic fields in muon-based material identification systems, a promising technology for security inspections. In this thesis, we also investigate the impacts of magnetic fields on scattering muography inspection systems.

Chapter 1 provides an in-depth look into the phenomenon of cosmic-ray muons and their creation processes. It introduces muography, describing its historical evolution, principles, detectors, and applications. Additionally, it gives an overview of the methods currently are being used for measuring magnetic fields. The chapter ends with defining the study objectives and providing an overview of the thesis.

In Chapter 2, the methodology is discussed, delving into the motion of muons in a magnetic field and the models for cosmic-ray spectrums, including the PARMA model. This chapter also explores the interactions of muons with matter and presents the tools used for particle transport.

Chapter 3 focuses on magnetic field muography detectors. It describes and analyzes the transmission and deflection methods proposed for the magnetic field studies using cosmic-ray muons, detailing the specific techniques and considerations for designing detectors, and analyzing methods.

Chapter 4 presents feasibility simulations for the transmission and deflection methods in magnetic field studies. It further delves into the proposed methods for the estimation of magnetic flux density and concludes with a summary of the simulation results.

In the final chapter, Chapter 5, the main findings are summarized, and recommendations for future research are proposed. This chapter ends with concluding remarks that restate the importance and potential of this research area.

In conclusion, this thesis aims to address a gap in current understanding by investigating the feasibility and potential of cosmic-ray muons, or muography, for the detection, imaging, and measurement of magnetic fields. Despite the significant progress and potential exhibited by muography in various applications, its use in detecting magnetic fields remains largely unexplored. Furthermore, while existing magnetic field measurement techniques demonstrate impressive capabilities, they are not without limitations that necessitate the exploration of alternative approaches such as muography. This thesis reveals the potential of using cosmic-ray muons for magnetic field detection, showcasing a series of promising techniques that undoubtedly deserve further investigation. At the same time, it highlights the complexity and challenges involved in this new approach, underscoring the need for ongoing, focused research to fully tap into this potential and broaden our understanding of magnetic fields. We hope that our contributions will advance knowledge in this field and potentially pave the way for breakthroughs in the measurement and understanding of magnetic fields.