Atmospheric Charged $K/\pi$ Ratio and Measurement of Muon Annual Modulation with a Liquid Scintillation Detector at Soudan

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We report a measurement of muon annual modulation in a 12-liter liquid scintillation detector with a live-time of more than 4 years at the Soudan underground facility. Muon minimum ionization in the detector is identified by its observed pulse shape and large energy deposition. The measured muon rate in the detector is $28.69 \pm 0.02$ muons per day with a modulation amplitude of $2.66 \pm 1.0\%$ and a phase at Jul 22 $\pm 36.2$ days. This annual modulation is correlated with the variation of the effective atmospheric temperature in the stratosphere. The correlation coefficient, $\alpha_T$, is determined to be $0.876 \pm 0.614$. Correspondingly, a Geant4 simulation of the primary cosmic rays with energy up 100 TeV was implemented to study the correlation of the atmospheric charged kaon to pion ($K/\pi$) ratio and the muon annual modulation for muon energy greater than 0.5 TeV. We rule out that a $K/\pi$ ratio, 0.1598, different from 0.12 (determined by MINOS), at the production point 30 km above the Earth surface in the stratosphere can induce muon annual modulation at the depth of Soudan.

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I. INTRODUCTION

Energetic muons produced by the decay processes of pions and kaons in the stratosphere can reach deep underground. Numerous underground detectors discovered the annual modulation of muon rates $^{[11]}[13]$. This annual modulation is believed to be correlated with a slow temperature variation over seasons in the stratosphere where those muons are produced. Therefore, the muon flux underground has a dependency on the effective temperature of the stratosphere. An increase in the effective temperature in the stratosphere results in a lower density profile, which decreases the probability of pions and kaons interacting with the atmospheric particles. Consequently, more pions and kaons undergo decays, which increases the numbers of muons observed in a detector deep underground. Such a correlation between the measured muon flux underground and the effective temperature in the stratosphere was studied by several experiments such as AMANDA $^{[7]}$, Borexino $^{[8]}$, MACRO $^{[6]}$ and MINOS $^{[11]}$. It was suggested that measuring the correlation factor between the annual modulation observed in an underground detector and the temperature variation in the stratosphere can provide the information on the atmospheric charged kaon/pion ($K/\pi$) ratio $^{[14]}$. This is particularly interesting for an underground site where the observed muons from primary cosmic rays have energies greater than 7 TeV, since the Large Hadron Collider $^{[15]}$ only provides a collision energy of $\sim$7 TeV. Therefore, the phenomenon of the correlation between the muon annual modulation in an underground detector and the temperature variation in the stratosphere deserves more experimental and theoretical investigations to understand the expected local behavior of the atmospheric temperature effect and the difference in the muon flux over a long period of time. Such a strong correlation over a long period of time indicates a stable atmospheric charged $K/\pi$ ratio, which could shed light on the energies of the primary cosmic rays, and opens a new window for high energy cosmic ray astronomy.

To monitor the long term flux variation at a deep underground site, a liquid scintillation detector has been deployed at the Soudan underground facility (2100 m.w.e) and run there for over 4 years. It consists of a meter long and 5 inches in diameter aluminum tube, filled with 12 liters EJ-301 liquid scintillator. Two 5-inch Hamamatsu PMTs (R4144) are attached to both ends of the tube through Pyrex windows to collect the scintillation light. Detailed calibration procedures and techniques are discussed in Ref. $^{[16]}[17]$. In a separate paper, we have reported the observation of annual modulation induced by $\gamma$ rays from $(\alpha,\gamma)$ reactions at the Soudan Underground Laboratory $^{[18]}$. In this paper, the variation of the muon rate underground correlating with the modulation of atmospheric temperature is studied with both experimental data over 4 years and the Monte Carlo simulation of the primary protons with energies up to 100 TeV.

II. THE VARIATION OF MUON RATE AT THE SOUDAN UNDERGROUND FACILITY

The experiment with a 12 liter liquid scintillation detector was conducted at the Soudan underground facility with a live-time of 982.1 days over 4 years. The detector is calibrated from 1 MeV to 20 MeV by using gamma ray sources $^{22}$Na (1.275 MeV), AmBe (4.4 MeV), and the minimum ionization peak from cosmic muons (20.4 MeV) $^{[10]}$. The energy response to the entire energy range is
I modulation amplitude time. The formula we use to determine the fractional sphere at a given atmospheric depth $X$ is defined as:

$$\alpha_{\text{eff}} = \frac{\int_{0}^{\infty} dXT(X)W(X)}{\int_{0}^{\infty} dXW(X)}.$$ \hspace{1cm} (1)

Where $T(X)$ is atmospheric temperature in the stratosphere at a given atmospheric depth $X$, and the weight $W(X)$ is the temperature dependence of the production of mesons and their decay into muons that can be observed in our detector. The variation of atmospheric temperature in the stratosphere results in a change of the air density. Consequently, the change of the air density modifies the ratio of meson decays to hadronic interaction and the hence changing the muon flux observed underground. An effective temperature $T_{\text{eff}}$ can be defined as:

$$T_{\text{eff}} = \frac{\int_{0}^{\infty} dXT(X)W(X)}{\int_{0}^{\infty} dXW(X)}.$$ \hspace{1cm} (1)

We denote the correlation of the percentage variation in the observed muon rate $\Delta I_{\mu}/<I_{\mu}>$ correlates with the change in effective temperature $\Delta T_{\text{eff}}/T_{\text{eff}}$ is shown in Figure 3. The fitted result determines the value of $\alpha_T = 0.876 \pm 0.614$. The large uncertainty associated with the value of $\alpha_T$ measured in this work is governed by the limited statistical error per bin (4 days with 111 muons per bin).

Figure 4 summarizes the measured values for $\alpha_T$ from various underground depths. The reported values at different underground sites agree with the predicted $\alpha_T$ (red curve in Figure 4) well. Our detector is adjacent to the MINOS far detector at the same depth level of the Soudan underground facility. Both results show a good agreement with the prediction.
FIG. 3: The variation of muon rate $\Delta I_\mu/\langle I_\mu \rangle$ as a function of $\Delta T_{eff}/\langle T_{eff} \rangle$. The slope of the linear fit gives $\alpha_T = 0.876 \pm 0.614$.

FIG. 4: Measured of $\alpha_T$ at various detector depth. The red line is the value predicted including muon production by pions and kaons. The dashed curves above and below stand for pions or kaons only, respectively.

III. SIMULATION OF THE MUON RATE ANNUAL MODULATION WITH A GIVEN $K/\pi$ RATIO

A. Simulation of muons from primary cosmic rays

As observed in Figure 2, the muon rate modulates over a year period. The correlation with the variation of temperature is demonstrated in Figure 3. In the summer time, the temperature in the stratosphere increases. As a result, the air density decreases. Therefore, more mesons undergo decay processes to produce more energetic muons, which can be observed in a detector underground. In contrast to the summer, the temperature in the stratosphere decreases in the winter time, which increases the air density. Thus, more mesons can interact with air particles to produce muons with lower energies, which cannot reach a detector deep underground. This phenomenon is observed as the muon rate annual modulation in a detector underground. Since kaons ($K^+$ and $K^-$) have a shorter half-life (12.4 ns) than pions (26 ns for $\pi^+$ and $\pi^-$) [25], it is expected that this phenomenon is mainly due to the change of the fraction of pions that undergo decays with respect to the interactions with air particles [14] in the stratosphere. Accordingly, the correlation between the observed muon rate annual modulation and the variation of temperature in the stratosphere is sensitive to the $K/\pi$ ratio in the production place. As a result, measuring this correlation provides an indirect way to measure the $K/\pi$ ratio induced by very high energy cosmic rays in the stratosphere.

The atmospheric $K/\pi$ ratio was first measured using the MINOS-FD data in 2009 [11]. The measured $\alpha_T$, $0.873 \pm 0.009$ (stat) $\pm 0.010$ (syst) was used to determine the $K/\pi$ ratio together with the theoretical prediction with large errors up to 40% [26]. The determined atmospheric $K/\pi$ ratio is $0.12_{-0.05}^{+0.07}$. To examine the correlation between the observed muon rate annual modulation and the variation of temperature in the stratosphere, a simulation is performed to reproduce the surface muons originating from primary cosmic rays.

Primary cosmic ray protons (only) are generated at the top surface 100 km above sea level. We cast the proton energy range from 1GeV to 100 TeV with the differential spectral index to be -2.7. The U.S. 1976 Atmosphere Model [27] has been adopted to simulate the average air density and pressure change along with the altitude as shown in Figure 5. The seasonal air density variation from the Integrated Global Radiosonde Archive
FIG. 6: Shown is the seasonal air density variation obtained from IGRA for the location close to Soudan.

FIG. 7: Simulated muon energy spectrum at sea level compared with the measurement [29].

(IGRA) for the location which is very close to Soudan [28] is adopted in the simulation. As an example, we show the seasonal air density variation in the stratosphere at the level of 30 km above sea level in Figure 6. The Geant4 module physics QGSP_BERT_EMV with the step length 10 cm is applied in the simulation to reveal small perturbations of atmospheric weights caused by the variation of temperature.

B. Simulation results

Figure 7 shows the simulated cosmic ray muon energy spectrum in comparison with the measurement [29]. Cosmic muons are secondary particles from cosmic ray air shower events. Muons reaching the sea level are collected and the simulated energy spectrum is compared with the experimental data (see FIG. 7).

For our experimental setup, only those surface muons with energy greater than 500 GeV can reach the underground depth where our detector is located. The parent particle of those muons are cosmic ray $k\pm$ and $\pi\pm$. The $K/\pi$ with their energy greater than 500 GeV is counted as: 0.1598. The average energy conversion between the parent $k\pm, \pi\pm$ and secondary muons are shown in FIG. 8. Most of decays of $k\pm$ and $\pi\pm$ are found to be around 20–30 km above the sea level.

With a $K/\pi$ ratio of 0.1598 in the simulation and the seasonal air density variation shown in Figure 5 the muon rate annual modulation is not observed in the simulation for muons with energies up to 0.5 TeV and 0.7 TeV as shown in Figure 9 and Figure 10. The results from the simulation indicate that the $K/\pi$ ratio of 0.1598 is not a correct ratio to generate the sufficient muon rate annual modulation observed in a detector at the Soudan underground facility.
IV. CONCLUSIONS

Our detector has been running at the Soudan underground facility (2100 m.w.e.) for over four years. Data analysis gives a muon flux \( I_\mu = (1.65 \pm 0.12) \times 10^{-7} \text{cm}^{-2} \text{s}^{-1} \). Seasonal modulation of muon rates are observed with the percentage amplitude of 2.66% and the phase to be Jul 22 ± 36.2 days. The correlation between atmospheric temperature variations and the changes in the muon rates observed in our detector has been investigated. The temperature coefficient of \( \alpha_T = 0.876 \pm 0.614 \) is found for the underground depth where our detector is located. This result is in good agreement with the measurement made by the MINOS-FD. The value of \( \alpha_T \), 0.876, implies that the atmospheric \( K/\pi \) ratio is 0.12 in the stratosphere determined by the MINOS-FD. We rule out a different \( K/\pi \) ratio of 0.1598, which can contribute to the observed muon annual modulation in a detector at the Soudan underground facility.

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