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Effective Temperature Calculation and Monte Carlo Simulation of Temperature Effect on Muon Flux*

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Abstract Many experiments have reported observations on possible correlations between the muon flux and temperature variation in the atmosphere, and especially recent MACRO and AMANDA observed apparent seasonal variation in the absolute muon rate. We report the calculation of effective temperature from Payerne meteorological data, and the simulation of temperature effect on muon flux from its representative atmosphere samples, which gives temperature coefficient α_T prediction in muon threshold energy range 30 GeV up to 2000 GeV and the order of possible influence on absolute muon flux.

Key words temperature effect, effective temperature temperature coefficient, muon flux

1 Introduction

Muons on the Earth originate primarily from the decay of mesons created in high energy interactions between primary cosmic ray particles and atmospheric nuclei. And fluctuations of meteorological conditions such as pressure and temperature etc. in the atmosphere lead to variations in the muon intensity observed at ground level and underground. But it has been shown to be at least an order of magnitude smaller for the pressure effect than that of temperature above about 30 GeV[1]. The temperature effect has been known since early in the history of cosmic ray physics[2—6], and has been well studied by Ref.[1] of above ground cosmic ray experiments; underground measurements are not often in agreement with theory, especially the energy range from 10 GeV to 500 GeV[7—15], but recent underground MACRO[16] (3800 M.W.E., ~1.3 TeV) and Antarctic-ice AMANDA[17] (1590 M.W.E., ≥500 GeV) results are consistent with measurements by other experiments[3,7,13] and with the theoretical expectation based on 'effective temperature' concept and approach by Barrett et al[3,16,18].

There has been an underground muon spectrometer[19] to be employed for the study of cosmic ray muons[20], which has high momentum resolution and a large sensitive volume, being sensitive to muons with wide energy range. So it's expected for such experiments to give temperature coefficient in a certain energy range with good momentum resolution compared with already existed almost only one energy threshold experiments, and especially the results in the low energy range which some former experiments divert the theoretical curve apparently. Also very important to such experiments is that the investigation of temperature effect is very useful for precise determination of muon spectrum, estimating the systematic error from temperature factor or using as a parameter to cut and select data or even correct temperature effect on absolute muon flux.

In this paper the calculation of effective temperature for the study of temperature effect on muon flux will be introduced, and Monte Carlo simulation on temperature effect and possible influence on muon flux also be reported.

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2 Calculation of effective temperature

Detailed meteorological data are obtained in balloon flight at Payerne/Switzerland and made available by "Service de climatologie"[21]. Balloons are launched at least two times a day of the year 1999 and 2000: at 0:00 and 12:00 hours (for most days in 1999, there were two additional times: at 6:00 and 18:00 hours). The measurement records altitude, temperature and pressure, as well as other parameters during its acension. The balloon rises to varying altitudes, and mostly it reaches about 35km, as seen in Fig.1.

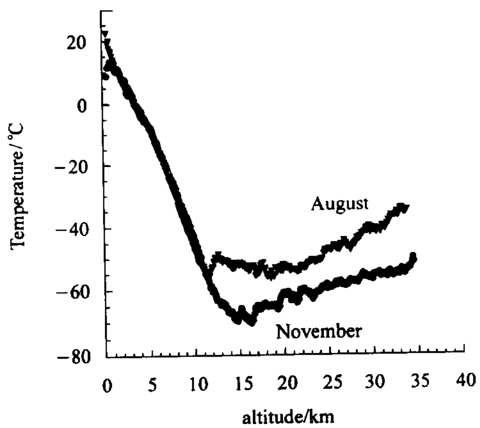

Fig.1. Temperature profiles of Payerne (about 100km away form Geneva, Switzerland) meteorological data: Aug.11 and Nov.5[22].

The dependence of muon intensity variations on the atmospheric temperature is often expressed phenomenologically as[3]:

$$\frac{\Delta I_\mu}{I_\mu^0} = \int_0^{X_0} \mathrm{d}X\alpha(X)\frac{\Delta T(X)}{T(X)}, \tag{1}$$

where $I_\mu^0 = I_\mu(T_0, > E_{\mathrm{th}})$ is the muon intensity integrated from certain energy threshod E_{th} to infinity assuming the atmosphere is isothermal at a certain temperature T_0, and ΔI_μ is the fluctuation around a nominal intensity I_μ^0 due to temperature variation; $\alpha(X)$ is the temperature coefficient density, and $\Delta T(X)$, the temperature fluctuation of temperature $T(X)$ at a given atmospheric depth X. The integration is performed across the whole atmosphere for ground or underground experiments or, more concrete, from the altitude of muon production to the observational level X_0. As discussed in Ref.[16], an effective temperature T_{eff} can be defined to replace Eq.1 by:

$$\Delta R_\mu/\bar{R}_\mu = \alpha_{\mathrm{T}} \cdot \Delta T_{\mathrm{eff}}/\bar{T}_{\mathrm{eff}}, \tag{2}$$

where α_{T} is temperature coefficient, R_μ and T_{eff} are the counting rate of muons and effective temperature, respectively, and their mean $\bar{R}_\mu$ and $\bar{T}_{\mathrm{eff}}$ are taken over the period of observation. The effective temperature is defined[3,16] as:

$$T_{\mathrm{eff}} = \frac{\int_0^{X_0}\mathrm{d}XW(X)T(X)}{\int_0^{X_0}\mathrm{d}XW(X)}, \tag{3}$$

a weighted value of the temperature at different depths, and can be seen as the temperature of an isothermal atmosphere resulting in the same intensity of muons as the produced in an atmosphere having a temperature distribution $T(X)$[3]. And the weight is given as[18]

$$W(X) = \frac{\Lambda}{X}[\exp(-X/\Lambda_\pi) - \exp(-X/\Lambda_{\mathrm{N}})], \tag{4}$$

where $\Lambda = \Lambda_\pi\Lambda_{\mathrm{N}}/(\Lambda_\pi - \Lambda_{\mathrm{N}})$, Λ_π and Λ_{N} are separately the attenuation lengths for pions and for nucleons. Eq.(4) is valid if scaling limit is applied and muons from kaon decay's contribution are neglected[16].

If kaon's considered, it looks like[23]:

$$W(X) \sim \frac{Z_{\mathrm{N}\pi}}{1 - Z_{\mathrm{NN}}} \cdot \frac{\Lambda_\pi}{\Lambda_\pi - \Lambda_{\mathrm{N}}}(\mathrm{e}^{-X/\Lambda_\pi} - \mathrm{e}^{-X/\Lambda_{\mathrm{N}}}) + \frac{Z_{\mathrm{NK}}}{1 - Z_{\mathrm{NN}}} \cdot \frac{\Lambda_{\mathrm{K}}}{\Lambda_{\mathrm{K}} - \Lambda_{\mathrm{N}}}(\mathrm{e}^{-X/\Lambda_{\mathrm{K}}} - \mathrm{e}^{-X/\Lambda_{\mathrm{N}}}), \tag{5}$$

where Z_{ij} is the spectrum-weighted moment, which determines the uncorrelated flux of particles j produced by particle i in the atmosphere[18]. All these approximations hold separately for Eq.(4) when $E_{\mathrm{th}} \gg \epsilon_\pi$ and Eq.(5) when $E_{\mathrm{th}} \gg \epsilon_{\mathrm{K}}$ ($\epsilon_\pi = 115\mathrm{GeV}$ and $\epsilon_{\mathrm{K}} = 850\mathrm{GeV}$, the critical energy for π and K, respectively), and at low energies where $E_{\mathrm{th}}\cos\theta \ll \epsilon_\pi$ (at the slant cases, θ for zenith angle), substituting Eq.(4) the weight becomes[23]

$$W(X) \sim \frac{Z_{\mathrm{N}\pi}}{\lambda_{\mathrm{N}}}\mathrm{e}^{-X/\Lambda_{\mathrm{N}}} \cdot X, \tag{6}$$

where the λ_{N} is the mean interaction length for nucleons in the atmosphere. As indicated in Ref.[23], Eq.(5) or Eq.(6) does not too much change the Eq.(4) s result and only result in systematic deviation within 0.1 % and 0.6 %, respectively, for different energy threshold, so these considerations are neglected. These assumpations are sufficient for the resolution we seek to achieve in our present α_T measurement. At low energies (below a few GeVs), muons are sensitive to pressure changes which alter their energy-loss by ionization, and the ground flux is thus changed also due to their limited life-time at low energies. These two effects lead to a negative correlation between temperature and pressure and the muon intensity, but are negligible in our analysis for higher energy threshold above 30 GeV.

The atmopheric depth profile of atmosphere is extracted from our direct pressure data measured at every ballooon release: $X(h) = p(h)/g$, where p is the pressure value at the altitude h, and g the gravitational accelerate constant. Then the dynamic weight is getten to the real cases of changing conditions of atmosphere of every flight's measurement. Fig.2 gives profiles of atmopheric depth (left) and corresponding weight with the altitude (right).

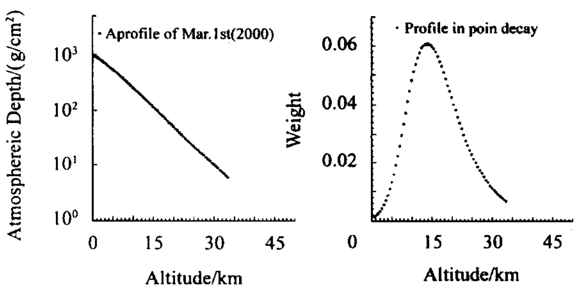

Fig.2. Atmospheric depth vs. altitude: a profile directly from pressure data (left), and corresponding weight with altitude (right).

Since it's known that the temperature keeps on rising from about 20km to the upper layers of the stratosphere at around 50km upto which the weight cannot be neglected as shown in the right plot of Fig.2, so the measured data above 25km are used to fit a straight line to extrapolate this height, which have a linear approximation with the altitude as seen in Fig.1; and the pressure data are treated in the same way to the same height but are fitted in log scale linearly with the altitude.

Instead of integrating, summing is performed with the meteorological data on Eq.(3) with the weight from Eq.(4), and the final T_{eff} of every release is calculated. Some individual points of T_{eff} scattering by more than one or two degrees around the 'main stream' are probably due to poor measurements, indeed mostly because of a reduced maximum height of that particular balloon flight. So a smoothing algorithm[22] is developed to suppress outliers and give every day's result, and the fluctuations of single points are reduced but the significant peaks and dips are retained. Fig.3 shows the final T_{eff} of the two years of our calculation.

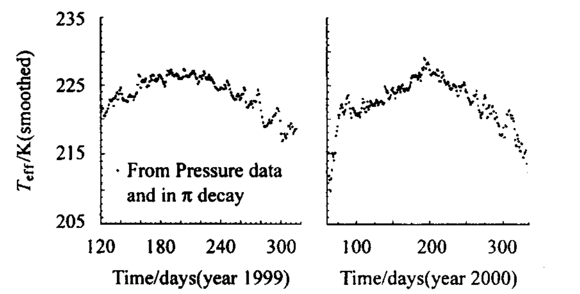

Fig.3. T_{eff} of year 1999 and 2000 at Payerne.

3 Monte Carlo simulation and α_T prediction

3.1 Atmosphere samples

The atmosphere conditions are described by parameterized atmospheric mass depth in simulation programme[24,25], and temperature information can be drawn from the atmospheric mass depth distribution[22]. In simulation with COMUGEN[25] we use the same parameterization technique as that in Ref.[24], and the atmosphere is subdivided into five layers ($i = 1,2,\cdots,5$), the four lower ones (up to 100km) are parameterized as

$$X(h) = a_i + b_i \cdot e^{-h/c_i}. \tag{7}$$

The four layers end at 4km, 10km, 40km and 100km, respectively, and for the fourth layer (40—100km) a_4 is fixed to 0 as that of Standard American Atmosphere in CORSIKA[24], seen as one of flat behaviour from 40km to 100km in upperleft plot of Fig.5. From Payerne meteorological data of the year 1999, 8 representative days' atmosphere samples are selected: July 22, Aug. 4, Aug. 24, Sep. 10, Sep. 24, Oct. 8 and Oct. 11, with the effective temperature decreasing nearly with an equal value. The temperature can be calculated as[23]

$$T(h) = C \cdot p(h) \cdot \left(\frac{dp(h)}{dh}\right)^{-1} \equiv C \cdot X(h) \cdot \left(\frac{dX(h)}{dh}\right)^{-1} \tag{8}$$

with the constant $C = g \cdot \frac{\rho^0 \cdot T^0}{p^0} = 0.03418\text{K/m}$, where

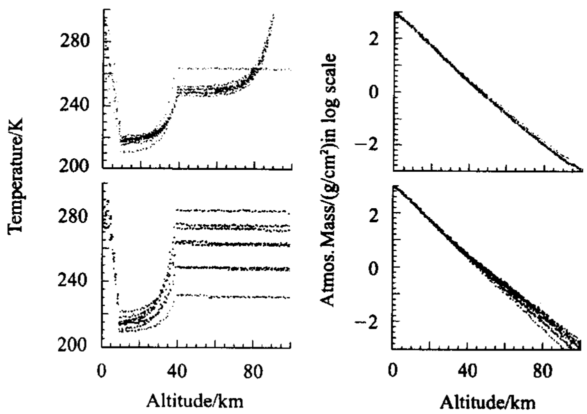

Fig.4.　Parameterized atmospheric depth (right) and corresponding calculated temperature profiles (left) with altitude. Upper plots for atmosphere samples in CORSIKA[24]; low ones for Payerne 8 representative samples, and the dotted lines from top to bottom are for: July 22, Aug. 4, Aug. 24, Sep. 10, Sep. 24, Oct. 8 and Oct. 11, respectively.

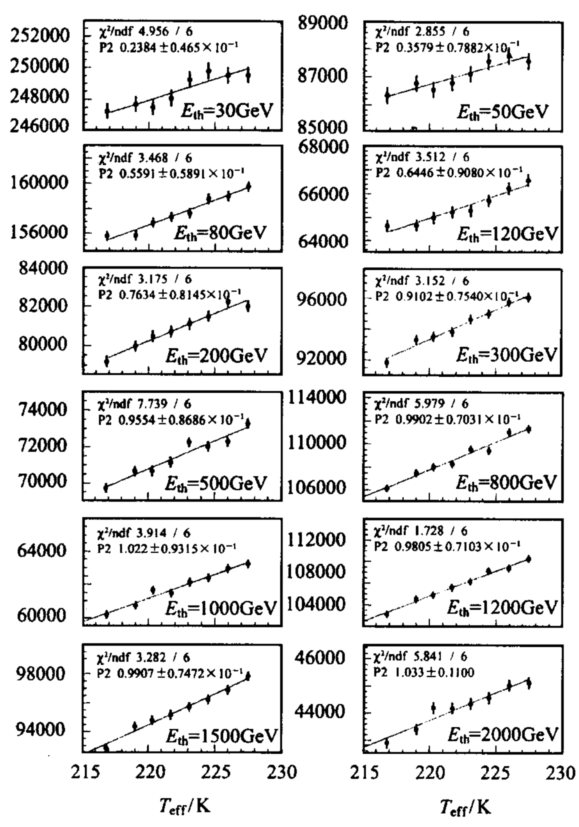

Fig.5.　Muon counts vs. effective temperature of different atmosphere samples under different energy thresholds.

air density is $\rho^0 = 1.293\text{kg/m}^3$ under the standard pressure ($p^0 = 1.01325 \cdot 10^5\text{Pa}$) and temperature ($T^0 = 273.15\text{K}$). The resulting pressure and derived temperature profiles are shown in Fig.4. It's noticed that the varied profile of samples in CORSIKA assume different behaviour to these of Payerne's from 10km to 40km, but not to be discussed here.

3.2 COMUGEN prediction

In simulation, the high energy hadronic interaction model Mini-jet and low energy model Scaling are selected; protons are produced with a spectral index of -2.7 and zenith angles below 30 degree, and the observation takes place at the altitude of 449 m above sea level with respect to the detecter position of Ref.[20]. The samples of each atmosphere are simulated with different primary energy ranges in order to optimize the sampling density.

Fig.5 shows plots of the muon production count as a function of the effective temperature under different energy threshold.

Fit with straight line of the form

$$R = R_0 \cdot \left(1 + \alpha_T \cdot \frac{T_{\text{eff}} - \bar{T}_{\text{eff}}}{\bar{T}_{\text{eff}}}\right) \tag{9}$$

allows to determine the temperature coefficient α_T as a function of muon energy threshold. The results are in agreement with the theoretical prediction given by the formula of Eq.(10)[3,16], shown in Fig.6 as points and curves in addition to experimental results adapted from Ref.[16] and AMANDA[17].

$$\langle \alpha_T \rangle_\pi = 1\Big/\left\{1 + \frac{\gamma}{(\gamma + 1)} \times \frac{\epsilon_\pi}{1.1 E_{\text{th}} \cos\theta}\right\}, \tag{10}$$

where γ is the spectral index for observed muons and we take 2.0 the value around 100GeV. The results of

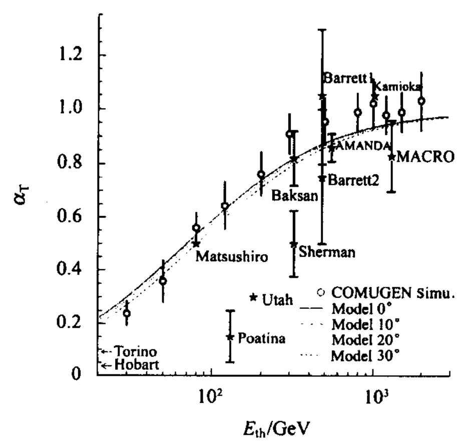

Fig.6.　COMUGEN simulated α_T with the expected theoretical curves from Eq.(10), in addition to experimental results adapted from Ref.[16] and AMANDA[17].

Sherman[8], Poatina[11] and Utah[12] deviate significantly from both the theoretical curves and M.C., and Ref. [16] considers this likely due to their choice of T_0 from lower altitudes, 100—300 mb (for these experiments, the measurements are reported as α_T/T_0 in units of %/K); other experimental results are consistent with theoretical curves or M.C. results. At low energy threshod around 10 GeVs, the results of Torina and Hobart also consistent with theoretical prediction when the correction for muon decay to electrons is taken from Barett et al.[3], only designated but not shown in Fig.7.

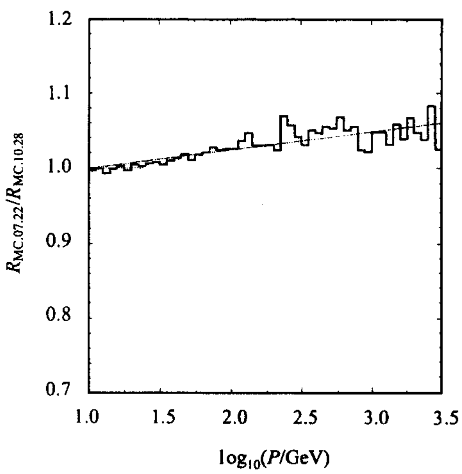

Fig.7. The ratio of muon production under two extreme T_{eff}: a high one of July 22 and a low one of Oct. 28 of year 1999.

Fig.7 gives the ratio of muon production under two extreme T_{eff} in 1999: the day of July 22 with a high one and the day of Oct. 28 with a low one. It shows that the variation of muon flux increases with the muon energy, about 2.5% at 100GeV to 5% at 1000 GeV with T_{eff} difference of 11 K.

4 Conclusion

We extract the effective temperature from Payerne meteorological data which can be used to calculate temperature coefficient for the study of temperature effect on muon flux, and also muon spectrum data analysis with the experiment of Ref.[20]. What we have done are based on theoretical calculation and reasonable approximation. With 8 representative atmosphere samples, we simulate the corresponding muon productions and calculate the temperature coefficient, which is a good test on the concept of effective temperature and related theoretical prediction.

The Monte Carlo of this work also give us the direction of real extraction of temperatue coefficient, and especially the order of magnitude on possible influence of temperature variation on muon flux near the Payerne region.

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有效温度的计算和大气 μ 子温度效应的 Monte Carlo 模拟*

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摘要　高空大气气温变化引起地面或地下探测到的宇宙线 μ 强度变化. 本文介绍了基于日内瓦附近 Payerne 气象站气球数据的大气 μ 子有效温度的计算,并选取代表性的 8 个大气样本模拟了 L3 + Cosmics 探测器位置的宇宙线 μ 子温度效应,计算了温度系数,得到极端高空温度情况下可能探测到的 μ 子强度变化的量级,为 L3 + Cosmics μ 谱精细测量和温度系数的抽取提供参考.

关键词　温度效应　有效温度　温度系数　μ 子强度

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