Study of meson production in the atmosphere using muons in MINOS

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***Abstract*. Muons in the atmosphere come predominantly from π and K decay. In the upper atmosphere where most underground muons are produced, the critical energies at which the meson interaction and decay are equal are ϵ_π = 115 GeV and ϵ_K = 850 GeV. The study of muons underground can be used to study meson production in the atmosphere. Methods to be used include the study of the atmospheric muon charge ratio, and seasonal effects.**

***Keywords*: meson production, muons**

I. THE ATMOSPHERIC MUON CHARGE RATIO

The measured charge ratio in a bin of surface muon energy and zenith angle can then be expressed as[1]

$$r = \frac{N^{\mu^+}}{N^{\mu^-}} = \frac{\left\{ \frac{f_\pi}{1+\frac{1.1 E_\mu \cos\theta}{115 \text{ GeV}}} + \frac{0.054 \times f_K}{1+\frac{1.1 E_\mu \cos\theta}{850 \text{ GeV}}} \right\}}{\left\{ \frac{1-f_\pi}{1+\frac{1.1 E_\mu \cos\theta}{115 \text{ GeV}}} + \frac{0.054 \times (1-f_K)}{1+\frac{1.1 E_\mu \cos\theta}{850 \text{ GeV}}} \right\}} \quad (1)$$

f_M is the fraction of that meson which are positive. f_π is greater than 0.5 because primary cosmic rays are primarily positively charged protons. f_K is even higher because ΛK^+ is kinematically strongly favored over K^+K^- production in hadronic interactions. An explanation of all of the constants can be found in Reference [2].

An interesting feature of Equation 1 is that it depends only on $E_\mu \cos\theta$ and not otherwise on E or θ. This combination of terms controls the relative portions of interaction and decay for both π's and K's. Thus at a fixed value of $E_\mu \cos\theta$ the ratio of μ's from π's and K's is constant.

At the last ICRC in Mexico, the MINOS collaboration reported a high statistics measurement of the charge ratio with $E_\mu \cos\theta$ near 1 TeV which showed a compelling rise in the charge ratio for the first time[3]. Together with precise data from the L3+C Collaboration[4] and/or the MINOS near detector[5], the data has been fit and the $r_\pi = f_\pi/(1-f_\pi) = N(\pi^+)/N(\pi^-)$ and $r_K = f_K/(1-f_K) = N(K^+)/N(K^-)$ values extracted.

In interpreting Equation 1 to extract r_π and r_K, some other effects need to be taken into account. The energy loss for μ^+ and μ^- are slightly different, so the measured ratio underground is not the same as the ratio at production. For MINOS this corresponds to a correction so that r_μ at the surface would be 0.6% higher than the value measured underground. For lower slant depth, the effect is smaller.

Another effect which has been studied is the possibility that primary cosmic ray Helium nuclei have a different spectral index from protons. This would change the neutron to proton ratio as a function of Energy (not $E_\mu \cos\theta$). This possible effect has been studied in References [6] and [7]. The effect lowers the charge ratio, so it implies a higher r_K for a given measurement of r_μ.

II. SEASONAL EFFECTS ON THE UNDERGROUND MUON RATE

Equation 1 assumes a given π/K ratio independent of energy. The correlation of the variation of the muon rate with effective temperature in the atmosphere allows a possibility to measure this ratio, independent of the charge ratio. Again it is the different values of ϵ_π and ϵ_K which allows this measurement. Seasonal variations in muon intensity underground have been seen by the MINOS far detector[8], and also previously by MACRO[9]. At this conference, a seasonal effect from the MINOS near detector, which has a much smaller overburden, is being reported[10]. Muons which come from a parent meson and which have $E_\mu \cos\theta$ above ϵ are more highly correlated than those from lower $E_\mu \cos\theta$. Since the value of ϵ differs for πs and Ks, a measurement of the actual correlation can be used to estimate the relative contribution, and hence the π/K ratio. This method has been analytically described in Reference [8] and the result will be presented in Reference [11].

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