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A new contribution to the conventional atmospheric neutrino flux

Thomas K. Gaisser[a], Spencer R. Klein[b,c,*]

[a] Bartol Research Institute and Dept. of Physics and Astronomy, University of Delaware, Newark, DE, USA
[b] Lawrence Berkeley National Laboratory, Berkeley, CA, USA
[c] University of California, Berkeley, Berkeley, CA, USA

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ABSTRACT

Atmospheric neutrinos are an important background to astrophysical neutrino searches, and are also of considerable interest in their own right. This paper points out that the contribution to conventional atmospheric ν_e of the rare semileptonic decay of K_S becomes significant at high energy. Although the $K_S \to \pi e \nu$ branching ratio is very small, the short K_S lifetime leads to a high critical energy, so that, for vertical showers, the inclusion of K_S semileptonic decay increases the conventional ν_e flux by ≈30% at energies above 100 TeV. In this paper, we present calculations of the flux of ν_e from K_S. At energies above their critical energies, the ν_e fluxes from kaon decay may be simply related to the kaon semileptonic widths; this leads to a near-equality between the flux of ν_e from K^+, K_L and K_S.

1. Introduction

Atmospheric neutrinos are of interest for understanding cosmic-ray interactions in the atmosphere and as probes of physics, such as neutrino oscillations [1,2]. They are also an important background in searches for high-energy astrophysical neutrinos, particularly in searches for a diffuse flux. In diffuse searches, the significance of any signal depends critically on the assumed flux and spectral shape of the atmospheric neutrino background.

High-energy atmospheric neutrinos are typically divided into two classes: conventional and prompt [3]. Conventional neutrinos come from the decays of pions and kaons, and the muons produced when pions and kaons decay. Pions and kaons have lifetimes long enough so that, at energies above ≈1 TeV, they are likely to interact before they decay; the relative interaction probability increases linearly with energy, so the neutrino spectrum from decays at high energy is softer. At high energies, where most muons reach the ground before they decay, the principal sources of ν_e are the decays $K^+ \to \pi^0 e^+ \nu_e$ and $K_L \to \pi^- e^+ \nu_e (\pi^- e^- \bar{\nu}_e)$. It was pointed out recently that η and η' can decay to $\mu^+\mu^-$ and contribute to the conventional muon flux, but not to the neutrino flux [4].

Prompt neutrinos come from the decays of charmed and bottom hadrons. These particles decay quickly (critical energies $\sim 10^7$ GeV or higher) so the spectral index of neutrinos from their decays is similar to that of the primary cosmic-ray spectrum in the energy range considered here.

There have been many calculations of the conventional neutrino flux. Several analytic calculations exist, mostly using the method of Z-moments [3,5]. Other calculations use Monte Carlo simulations, often based on different hadronic interaction models [6–8].

In this work we evaluate the contribution of the rare, semileptonic decay of K_S to the flux of ν_e. This contribution has been neglected previously because of its low branching ratio, which makes its contribution negligible below 10 TeV. For the same reason, this channel is not tracked in CORSIKA [9]. Although the semileptonic branching ratio is very small, the K_s lifetime is very short, so that, in cosmic-ray air showers, it is more likely to decay than to interact. As a consequence, its contribution to the flux of ν_e is one power harder in energy than those from K_L and $K^\pm$, so that at sufficiently high energy it contributes a significant fraction of the total.

2. Electron neutrinos from K_S

The characteristic energy ϵ_i that characterizes whether an unstable particle is more likely to interact or decay in the atmosphere is

$$\epsilon_i = \frac{m_i c^2 h_0}{c\tau_i}, \tag{1}$$

where m_i and τ_i are the particles mass and lifetime, and h_0 is a scale height in the atmosphere, typically 6400 m [3]. The energy at which

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[*] Corresponding author at: Lawrence Berkeley National Laboratory, Berkeley, CA, USA.

E-mail addresses: gaisser@bartol.udel.edu (T.K. Gaisser), srklein@lbl.gov (S.R. Klein).

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hadronic interactions become important depends on the atmospheric density, which varies with zenith angle θ_z. Interactions become predominant at energies above the critical energy:

$$E_{\mathrm{crit}} = \epsilon/\cos(\theta_z). \tag{2}$$

If the particle energy is higher than E_{crit}, then it is likely to interact before it can decay. Below the critical energy for a given channel, the spectrum of neutrinos from kaon decays closely matches that of the cosmic-ray spectrum, roughly $dN/dE \approx E^{-2.7}$, with the neutrino taking an average of roughly 25% of the kaon energy for $K \to \pi e\nu$ decays. At energies above the critical energy, the increasing interaction probability softens the spectrum by E^{-1}, to $dN/dE \approx E^{-3.7}$. Table 1 shows the semi-electronic branching ratios and critical energies for different types of kaons, along with those of charmed hadrons for comparison.

The ν_e flux from K_S decay may be easily determined by reference to the ν_e flux from K_L decays. K_S and K_L are produced at the same rate in air showers, and the $K \to \pi e\nu_e$ kinematics are almost identical. At low energies, the K_S contribution to the atmospheric ν_e flux is small, reduced by the ratio of the branching ratios $K_S/K_L : 0.07/40.55 = 0.0017$. At higher energies, above 210 GeV/ $\cos(\theta_z)$, the spectrum of ν_e from K_L-decay softens to $E^{-3.7}$, while the spectrum of ν_e from K_S remains unchanged. Thus, the relative ν_e contribution increases linearly with the energy. At the K_S critical energy of 120 TeV/ $\cos(\theta_z)$, the ratio has increased by $\epsilon_{K_S}/\epsilon_{K_L} \approx 588$, and the K_S and K_L contributions to the ν_e flux are equal! This is not just a fortuitous numerical coincidence. It happens because the lifetime is inversely related to the total decay width, and the branching ratio is the ratio of the semileptonic width to the total width. With $\epsilon \propto 1/\tau = \Gamma_{tot}$ and $Br(K \to \pi e\nu) = \Gamma_{sl}/\Gamma_{tot}$, as long as the K_S and K_L are produced in equal numbers, the ratio of the ν_e fluxes for neutrino energies above the two E_{crit} is

$$\frac{\phi(\nu_e \text{ from } K_S)}{\phi(\nu_e \text{ from } K_L)} = \frac{Br(K_S \to \pi e\nu)}{Br(K_L \to \pi e\nu)} \frac{\epsilon_{K_S}}{\epsilon_{K_L}} = \frac{\Gamma_{SL}(K_S)/\Gamma_{Tot}(K_S)}{\Gamma_{SL}(K_L)/\Gamma_{Tot}(K_L)} \frac{(1/\tau_{K_S})}{(1/\tau_{K_L})} = 1. \tag{3}$$

A similar argument applies for $K^+ \to \pi^+ e\nu_e$, which has a similar mass and semileptonic width as the K_L and K_S. However, associated production in reactions like $pp \Longrightarrow K^+\Lambda p$ is different for K^+ than for the K^0 and $\overline{K}^0$ from which the K_L originate. As a consequence, the contribution of charged kaons to the flux of ν_e is not exactly equal to that of K_L.

Neglecting for the moment associated production, at energies $E_\nu > E_{\mathrm{crit}}$, the inclusion of K_s increases the ν_e flux by about 50%. For quasi-vertical angles of incidence, this increase occurs at energies of ≈100 TeV, which is the range in which most current searches for extra-terrestrial neutrinos are focused. At higher energies, the enhancement is large for a wider angular range, but the conventional ν_e flux is overshadowed by the prompt flux.

A similar enhancement occurs for ν_μ, via $K_S \to \pi\mu\nu_\mu$. However, because of the large ν_μ contribution from two-body decays of charged kaons and pions, it is much less significant. Figure 7 of [4] gives the relative contribution to ν_μ production of π^+, K^+, K_L and μ decay. K^+ decay dominates at energies above 500 GeV; the contribution from K_L is negligible, so, at higher energies, the K_S contribution will remain small.

There are additional ν_e contributions from the semileptonic decays of strange baryons like the Λ and Σ; some of these baryons have semileptonic branching ratios similar to that of the K_S. However, their production rates are lower, and the neutrino carries only a relatively small fraction of the incident baryon momentum. So, their contribution to the total flux should be small.

3. Flux calculations

We extend the flux calculation described in Ref. [11] to include the contribution of $K_S \to \pi e\nu_e$. The calculation is a generalization of the scaling solutions of the coupled cascade equations for hadronic cascades in the atmosphere [3] in which the spectrum weighted moments are allowed to depend on energy in order to take account of the non-power-law behavior of the primary spectrum (the knee). The Z-factors for production of charged kaons, for example, are generalized to

$$Z_{NK^\pm}(E) = \int_E^\infty \mathrm{d}E' \frac{\phi_N(E')}{\phi_N(E)} \frac{\lambda_N(E)}{\lambda_N(E')} \frac{\mathrm{d}n_{K^\pm}(E',E)}{\mathrm{d}E}. \tag{4}$$

Here $\lambda_N(E)$ is the nucleon interaction length, $\mathrm{d}n_{K^\pm}$ is the number of charged kaons produced in $\mathrm{d}E$ by nucleons of energy E', and $\phi_N(E)$ is the spectrum of nucleons. This method was proposed in Ref. [12], and is a good approximation if the energy dependences are smooth. Simple forms for the hadronic cross sections [13] are used to interpolate and extrapolate tabulated values [3] of the spectrum weighted moments. For the calculation of the neutrino fluxes the spectrum of nucleons per GeV/nucleon is needed, assuming validity of the superposition approximation in which bound nucleons produce mesons as if they were free. We use the spectrum of nucleons from Model H3a of Ref. [14].

The basic equation for the flux of $\nu_e + \bar{\nu}_e$ at sufficiently high energy so that the contribution from muon decay can be neglected ($>\sim$ 1 TeV/$\cos\theta$) is

$$\phi_\nu(E_\nu) = \phi_N(E_\nu) \times \left\{ \frac{Z_3 b_{K^+e3}(Z_{NK^+} + Z_{NK^-})}{1 + B_3 \cos\theta E_\nu/\epsilon_K} + \frac{Z_3 b_{K_Le3} Z_{NK_L}}{1 + B_3^* \cos\theta E_\nu/\epsilon_{K_L}} + \frac{Z_3 b_{K_Se3} Z_{NK_S}}{1 + B_3 \cos\theta E_\nu/\epsilon_{K_S}} \right\}. \tag{5}$$

Here $Z_3 \approx 0.134$ [5] is the spectrum-weighted moment for the K_{e3} decay at low energy (when $E_\nu \ll \epsilon_{K_x}$). The branching ratios b_{K_xe3} are for each kaon flavor to the K_{e3} mode, and Z_{NK_x} is the spectrum weighted moment for a nucleon to produce a kaon of type x. The denominator interpolates between the low and high-energy behavior, where low and high are defined relative to ϵ_{K_x} for each neutrino source. Explicitly,

$$B_3 \approx \frac{0.134}{0.061} \left(\frac{\Lambda_K - \Lambda_N}{\Lambda_K \ln\frac{\Lambda_K}{\Lambda_N}} \right) = \frac{Z_3}{Z_3^*} \left(\frac{\Lambda_K - \Lambda_N}{\Lambda_K \ln\frac{\Lambda_K}{\Lambda_N}} \right), \tag{6}$$

where $Z_3^* \approx 0.061$ [5] is the high energy value of the spectrum weighted moment for K_{e3} when the factor ϵ_{K_x}/E weights the decay by an extra power of $1/E$. Z_3 and Z_3^* account for the fraction of the

Table 1
Masses, semi-electronic branching ratios, lifetimes and characteristic energy for the different kaon types, and, for comparison, charmed hadrons [10,11].

Type	Mass (MeV)	Br ($K \to \pi e\nu$) (%)	Lifetime (s)	Characteristic energy (GeV)
K^+	493.6	5.04	1.24×10^{-8}	850
K_L^0	497.6	40.55	5.12×10^{-8}	210
K_S^0	497.6	0.07	0.90×10^{-10}	120,000
Charm	≈1800		$\approx 10^{-12}$	$\approx 4 \times 10^7$