Atmospheric muons and neutrinos in neutrino telescopes

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1 Introduction

Atmospheric muons and neutrinos are important for neutrino telescopes, both as background in the search for high-energy neutrinos of astrophysical origin and because they serve to calibrate the detectors. In addition, the atmospheric lepton spectra are intrinsically interesting because the large size of current and proposed neutrino telescopes will make it possible to extend the measurements of atmospheric muons and neutrinos beyond the reach of previous measurements. It may finally be possible to achieve a long-sought goal of cosmic-ray science by detecting the contribution to the atmospheric leptons from decay of charmed hadrons, the "prompt" neutrinos and muons. At energies much lower than ~ 100 TeV, the prompt component is hidden by the much more abundant contributions from decay of charged pions and kaons. The crossover energy is poorly known, a point I return to at the end of the paper.

2 Neutrino telescopes

Currently operating neutrino telescopes are Baikal [1], Antares [2] and IceCube [3]. AMANDA [4], the predecessor of IceCube at the South Pole, was turned off at the beginning of 2009. With a planned volume of one cubic kilometer, IceCube will be by far the largest operating neutrino detector. It is already running with 70% of its sensors installed and will be completed in 2011. There are plans for a still larger neutrino telescope in the Mediterranean Sea (Km3NeT) [5], and there are also plans to expand the Baikal detector [6].

A neutrino telescope like IceCube is optimized for high energy, where possible fluxes from astrophysical sources with hard energy spectra are expected to be above the background of atmospheric neutrinos, which have quite steep spectra. The detection mechanism is the same as for Super-K [7] and SNO [8], namely reconstructing events from Cherenkov light produced by relativistic charged particles in the detector. To achieve their large effective volume, however, the neutrino telescopes are coarsely instrumented with widely spaced optical sensors. IceCube, for example, will have about 5000 photomultiplier tubes, each 25 cm in diameter, viewing a cubic kilometer as compared to a low-energy neutrino detector like Super-K, which has 11,000 PMTs with twice the diameter looking at a volume some 30,000 times smaller.

The neutrino telescopes have the largest effective volume for muon neutrinos in the TeV range and above. This is because the multi-kilometer pathlength of $\geq$ TeV muons allows reconstruction of tracks initiated by charged current interactions of ν_μ outside the instrumented volume of the detector. In general, the strategy for neutrino telescopes is to select events coming up from below the detector, thus using the Earth as a filter to discriminate against the background of atmospheric muons from above. Events that start and/or end inside the detector can also be reconstructed, allowing the identification of the other neutrino flavors. Tau neutrinos, expected because of neutrino oscillations from distant astrophysical sources, but not from the atmosphere, are of particular interest [9, 10, 11].

To extend its reach at lower energy, a densely instrumented sub-array is being built in the deep center of IceCube [12]. The goal is to define a fiducial volume of several megatons in which neutrinos interactions from all directions can be identified, while also extending the reach of IceCube to include neutrinos in the 10 – 100 GeV range. The surrounding sensors of the rest of IceCube will be used as a veto.

Preliminary measurements of muon [13] and neutrino [14] spectra with data from the partially constructed (20% complete) IceCube in 2007 were reported at the International Cosmic Ray Conference, July 2009. The atmospheric neutrino spectrum measured with AMANDA with data taken from 2000 to 2006 [4] already extends to just above 30 TeV. The full IceCube will be large enough to extend measurements of atmospheric muons and neutrinos well beyond 100 TeV.

3 Atmospheric muons and neutrinos

Fluxes of secondary cosmic-ray leptons in the atmosphere can be described to a good approximation by a set of formulas in which each element corresponds to one of the processes involved in their production. The approximation is good to the extent that the incident cosmic-ray spectrum is a power law in energy and the inclusive cross sections for production of secondary hadrons obey Feynman scaling in the forward fragmentation region. In particular, for $\nu_\mu + \overline{\nu}_\mu$

$$\begin{aligned}\phi_\nu(E_\nu) &= \phi_N(E_\nu) \\ &\times \left\{\frac{A_{\pi\nu}}{1 + B_{\pi\nu}\cos(\theta)E_\nu/\epsilon_\pi} + \frac{A_{K\nu}}{1 + B_{K\nu}\cos(\theta)E_\nu/\epsilon_K}\right. \\ &\left. + \frac{A_{\mathrm{charm}\,\nu}}{1 + B_{\mathrm{charm}\,\nu}\cos(\theta)E_\nu/\epsilon_{\mathrm{charm}}}\right\}, \qquad (1)\end{aligned}$$

where $\phi_N(E_\nu) = dN/d\ln(E_\nu)$ is the primary spectrum of nucleons (N) evaluated at the energy of the neutrino [15, 16]. The three terms in brackets correspond to production from leptonic and semi-leptonic decays of pions, kaons and charmed hadrons respectively. The equation for muons is similar at energies sufficiently high ($>$ 100 GeV) so that energy loss and decay of muons in the atmosphere can be neglected. The numerator of each term is of the form

$$A_{Ni} = \frac{Z_{Ni} \times BR_{i\nu} \times Z_{i\nu}}{1 - Z_{NN}} \tag{2}$$

with $i = \pi^\pm$, K, charm and $BR_{i\nu}$ is the branching ratio for $i \to \nu$. The first Z-factor is the spectrum weighted moment of the cross section for a nucleon (N) to produce a secondary hadron i from a target nucleus in the atmosphere, and the second Z-factor is the corresponding moment of the decay distribution for $i \to \nu + X$. Thus, for example for $N + \text{air} \to K^+ + X$,

$$Z_{NK^+} = \frac{1}{\sigma_{N-\text{air}}} \int_0^1 x^\gamma \frac{\mathrm{d}\sigma_{NK^+}(x)}{\mathrm{d}x}, \tag{3}$$

where $x = E_{K^+}/E_N$ and $\gamma \approx 1.7$ is the integral spectral index of the incident spectrum of cosmic-ray nucleons.

The denominator of each term reflects an important physical property of meson decay in the atmosphere–the competition between decay and reinteraction of hadrons. The critical energy depends on the zenith angle θ of the cascade in the atmosphere, and is of the form

$$\frac{\epsilon_i}{\cos\theta} = \frac{m_i c^2 h_0}{\cos\theta\, c\tau_i}. \tag{4}$$

Here $h_0 \approx 6.4$ km is the scale height in an exponential approximation to the density of the atmosphere at high altitude. When $E_i < \epsilon_i/\cos\theta$ the mesons decay so that the low-energy neutrino spectrum has the same power law index as the primary cosmic-ray spectrum. At high energy, the contribution of each term gradually steepens so that asymtotically, the neutrino spectrum is one power steeper than the primary spectrum. The critical energies are

$$\epsilon_\pi = 115 \text{ GeV}, \; \epsilon_{K^\pm} = 850 \text{ GeV, and } \epsilon_{\text{charm}} \sim 5 \times 10^7 \text{ GeV}.$$

These differences lead to a characteristic pattern of the contributions of the various channels to the flux of neutrinos: first the pion contribution steepens, then the kaon contribution and finally (at much higher energy) the contribution from decay of charmed hadrons becomes the main source of neutrinos and muons in the atmosphere. In addition, the suppression of charged pion contribution to the neutrino flux starts early because the quantity $B_{\pi\nu} = 2.8$ in the denominator of the first term of Eq. 1 is anomalously large compared to the corresponding factors for strange and charmed

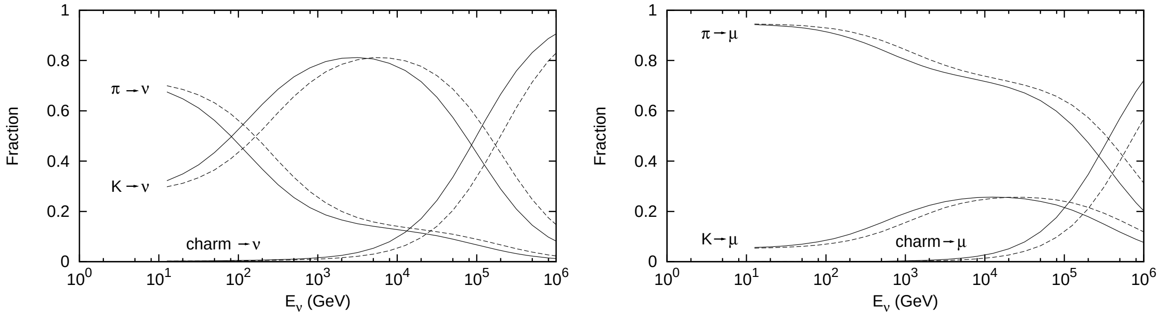

Figure 1: Left: Fraction of muon-neutrinos from pion decay, kaon decay and charm decay as a function of neutrino energy; Right: same for muons. Solid lines are for vertical and dotted lines for 60°. (See text for discussion.)

hadrons. This is a consequence of the kinematics of $\pi^{\pm} \rightarrow \mu^{\pm} + \nu$ decay in flight in which the muon carries most of the energy because its mass is comparable to that of the parent pion.

Fig. 1 shows the fractional contribution of the main hadronic channels to the production of neutrinos and muons in the atmosphere. Kaons actually become the dominant source of neutrinos above ~ 100 GeV. For muons, the dominant channel is never kaons, but the contribution of kaons does increase significantly in the TeV energy range. An interesting manifestation of the increasing importance of kaons at high energy is the measurement of the charge ratio of atmospheric muons with energies at production between 1 and 7 TeV in the far detector of MINOS [17]. The μ^+/μ^- ratio is observed to increase from its value of 1.27 around 100 GeV to ≈ 1.37 above a TeV. The increase is attributed to the importance of the associated production of kaons,

$$p + air \rightarrow \Lambda + K^+ + X, \tag{5}$$

which makes the $+/-$ charge ratio larger for kaons than for pions. Production of strange particles and anti-particles–in particular the process in Eq. 5–is highly asymmetric in the forward fragmentation region. Production of Λ is favored because it has constituents in common with the valence quarks of the proton.

4 Expectations for prompt leptons

At some energy, perhaps around 100 TeV or somewhat above, the decay of charmed hadrons will become the main source of all atmospheric leptons. Where the transition occurs is uncertain because of the wide variation in the literature on the level of charm production at large Feynman x. Like associated production of strangeness via

Eq. 5, the production of Λ_c^+ is also highly asymmetric in the forward fragmentation region. A measurement by the Fermilab Experiment 781 (SELEX) [18] shows that $(\sigma_c - \sigma_{\overline{c}}) / (\sigma_c + \sigma_{\overline{c}}) \approx 1$ for $0.2 < x < 0.7$ for 600 GeV protons on a fixed target. Here σ_c and $\sigma_{\overline{c}}$ represent respectively the production of Λ_c^+, which does, and $\overline{\Lambda}_{\overline{c}}^-$, which does not have valence quarks in common with the beam proton.

The quantitative implication of the forward production of open charm depends on the size of the cross section and its energy dependence. Ref. [19] surveyed the literature on charm production in their revision of the treatment of charm within the DPMJET event generator. DPMJET is based on the Dual Parton Model [20], which is related to the quark gluon string model [21], and is used in simulations of cosmic-ray cascades. For example, DPMJET is one of the options for event generation in CORSIKA [22], which is used for simulation of air showers by many groups, including IceCube. The paper of Ref. [19] adopts a fairly conservative value for the specific process of Λ_c^+ production, equivalent to ~ 10 μbarns for pp interactions.

Larger values are possible. For example a recent calculation [23] of charm (and beauty) production at accelerators within the DPM/QGSM framework uses a normalization based on two ISR measurements at $\sqrt{(s)} = 62$ GeV [24, 25]. The value of $\mathrm{d}\sigma/\mathrm{d}x$ is consistent with a value of 0.1 mb (with large uncertainty) around $x \sim 0.6$. Although the normalization inferred for the production of charm in the ISR experiments is considered unreliable [26], a value this large is still only a fraction of the total open charm production at this energy. (A summary of σ_{charm} is given in Ref. [19].)

It is instructive to make an estimate of the charm contribution to lepton fluxes in the atmosphere within the analytic framework of Eq. 1. For illustration I use the following numerical estimates, obtained by assuming that the differential cross section for production of Λ_c^+ is constant at 0.1 mb out to $x = 0.7$ and that $\gamma = 1.7$. Then $Z_{N\mathrm{charm}} = 0.0005$ and $Z_{\mathrm{charm}-\nu} \approx Z_{charm-\mu} \approx 0.13$. Assuming a similar distribution for the accompanying D-mesons, the total effective leptonic branching ratio is $BR_{\mathrm{charm}} \sim 0.14$. For the analytic approximation to be applicable, one must use an estimate of charm production in the forward fragmentation region that represents the high-energy limit in which Feynman scaling is a valid approximation. This supports the use of a relatively high normalization in this context. Fig. 2 shows the resulting prediction for vertical atmospheric muons and neutrinos. This simple analysis gives a relatively high level of charm production, which is still a factor of two lower than a calculation using the Relativistic Quark Parton Model [27]. This kind of picture with "intrinsic charm" was discussed already 30 years ago (e.g. Ref. [28]) when large values of forward charm production were first measured at the ISR. Calculations using perturbative QCD tend to give lower levels of charm production. As an example, a recent calculation within a perturbative QCD framework [29] is plotted in the right panel of Fig. 2.

It is conventional to multiply the differential energy spectrum of neutrinos and

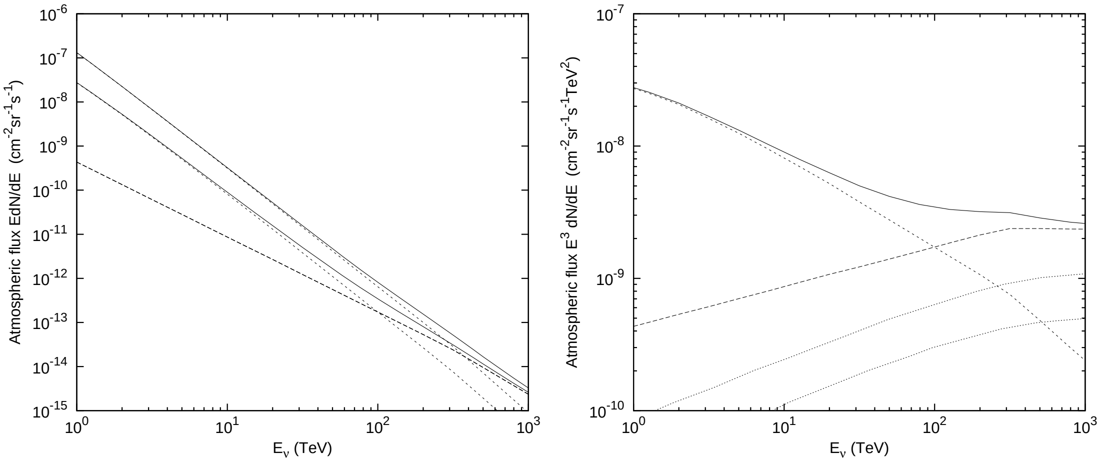

Figure 2: Left: Vertical flux of μ and ν_μ with contributions from decay of pions and kaons and from charm decay shown separately by broken lines. The upper solid line shows total $\mu^+ + \mu^-$ flux and the lower solid line the total flux of $\nu_\mu + \overline{\nu}_\mu$. Right: Flux of $\nu_\mu + \overline{\nu}_\mu$ multiplied by E^3. For comparison, the two parallel dotted lines show the range calculated in Rev. [29] for the contribution of charmed hadrons.

muons by three powers of energy in order to display details of the very steep spectrum, as in the right panel of Fig. 2. From the experimental point of view, however, it is important to note that the left panel is closer to what is actually measured. It shows $E \times \{\mathrm{d}N/\mathrm{d}E\}$, which corresponds to the number of events per logarithmic interval of energy. In reality, the hardening of the spectrum associated with the transition to prompt leptons is more subtle than the impression one has when the spectrum is multiplied by a high power of the energy. The experimental challenge is to measure the expected change in spectral index on a steeply falling spectrum with limited statistics. The challenge is greater because it is not possible to measure the full energy of the neutrino or the muon, but only the fraction of the energy deposited in the detector. Systematic effects of the detector must be well understood. In this connection it is relevant to note the different angular dependence of the two components, which is the traditional signature for distinguishing them. The prompt component is isotropic (up to $\sim 5 \times 10^7$ GeV) while the leptons from pion and kaon decay depend on zenith angle proportionally to $\sec\theta$.

In the neutrino sector one also expects a harder spectrum (γ approaching 1) of astrophysical neutrinos from extra-terrestrial sources. To the extent that individual sources are not resolved, either in direction or in time, an extra-galactic astrophysical component of high-energy neutrinos would also be isotropic. Such a diffuse, isotropic astrophysical component will be harder to identify the higher the level of charm production. In principle, a comparison of the muon flux with the neutrino flux should be able to resolve both the prompt atmospheric and the diffuse astrophysical component of the spectrum of atmospheric $\nu_\mu + \overline{\nu}_\mu$ because the muons originate only locally in the atmosphere.

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