Primary Cosmic-ray Spectrum and the Intensity of Atmospheric Neutrinos*

Thomas K. Gaisser
Bartol Research Institute, University of Delaware
Newark, DE 19716 USA

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Abstract

Measurements of the intensity of primary cosmic-ray protons reported in the last two years suggest a lower normalization than some earlier measurements. Here we comment on the measurements, compare them to the assumptions made in two independent calculations of atmospheric neutrinos and discuss the possible consequences for interpretation of measurements of atmospheric neutrinos.

In a series of recent papers [1, 2, 3], the Super-Kamiokande collaboration has presented evidence for neutrino oscillations based on a high-statistics sample of neutrino interactions in their large detector. The importance of these results, which consolidate and extend the previous discovery of an “atmospheric neutrino anomaly” [4, 5, 6, 7], calls for a new look at the calculation of the flux of atmospheric neutrinos, which is the starting point for interpretation of the data. I give a general analysis of the neutrino flux calculation elsewhere [8]. Here I consider only the primary spectrum, which affects mainly the normalization of the neutrino flux.

Neutrino interactions in Super-K are divided into sub-GeV [1] and multi-GeV [2] events. The most numerous are the sub-GeV events ($E_\nu \sim 1$ GeV), which come from primary cosmic rays with energy between 5 and 100 GeV/nucleon. The multi-GeV sample corresponds very roughly to a factor 5 to 10 higher neutrino energy and hence to a correspondingly higher range of primary energy. Neutrino-induced muons that enter the detector from below and stop cover a

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similar energy range to the multi-GeV sample. Finally, upward, through-going muons as measured by MACRO \[7\] and several other underground detectors, including the water detectors and Baksan \[4\], correspond to neutrino energies from $\sim 10$ to $\sim 10^4$ GeV and hence to primary energies up to $\sim 10^5$ GeV. For any one sample, uncertainty in the primary spectrum affects mainly the normalization. Because of the long lever arm in energy, however, a small uncertainty in the slope can have a significant effect on the calculated ratio of, for example, stopping to through-going muons.

The standard reference for the primary spectrum in the energy region responsible for the sub-GeV neutrino event sample was the work of Webber \textit{et al.} \[10\] until 1991. This was based on two balloon flights, one in 1976 and one in 1979, in which the spectra of hydrogen and helium were measured and compared. The LEAP experiment \[11\] flew in 1987 during solar minimum. It covered a similar energy range with the same spectrometer in a somewhat different configuration. The LEAP experiment gave results with a normalization for protons about 50% lower than the Webber results. This difference is larger than the uncertainty of either measurement and therefore implies the existence of systematic uncertainties that have not been fully understood. Since the atmospheric neutrino flux is proportional to the normalization of the primary spectrum, there is a corresponding ambiguity in the calculated flux of atmospheric neutrinos.

This was the situation until 1991 until about two years ago, when a series of magnetic spectrometer experiments started to appear in print. (See Table \[1\].) The results of these more recent experiments support the lower normalization of the LEAP measurement. The primary goal of these experiments was to measure the spectrum of cosmic-ray antiprotons. In the process, they necessarily measured the primary spectrum of protons and in most cases also of helium. Some of them also measured the spectrum of muons in the atmosphere during ascent as well as on the ground and at float altitude. The measured muon spectra are very closely related to atmospheric neutrino fluxes \[12\].

The IMAX \[13\] and CAPRICE \[14\] groups used modified versions of the same magnetic spectrometer as Webber \textit{et al.} and LEAP, but they were designed to provide two independent measurements of the trajectory through the spectrometer so that efficiencies could be determined with greater certainty. The most recent result is the BESS measurement \[15\] reported at this meeting. This experiment uses a completely different spectrometer and magnet with cylindrical geometry \[16\]. The BESS results also are in good agreement with the LEAP measurements.

A graphical summary of the BESS spectrum of hydrogen, together with a comprehensive compilation of the previous measurements is given in Ref. \[15\].

\[1\] There was also a flight of the MASS instrument but it occurred on September 5, 1989 during a record-breaking Forbush decrease, so it corresponds to an extremely high degree of solar modulation, and its interpretation is correspondingly complicated. In particular, its normalization is tied to that of the earlier measurement of Ref. \[10\].
Table 1: Measurements of primary cosmic-rays and atmospheric muons

| Year flown | Primary | Muons? |
|------------|---------|--------|
| Webber     | '76,'79 | p,He 10 | no |
| LEAP       | '87     | p,He 11 | no |
| MASS       | '89,'91 | p,He 14 | yes [18, 19] |
| IMAX       | '92     | p,He 13 | yes [20] |
| CAPRICE    | '94     | p,He 14 | yes [21] |
| BESS       | '97     | p 15    | not published [22] |
| HEAT       | '94,'95 |       | yes [23] |

Fig. 1 here shows another compilation of the measurements of primary spectra of nuclei in which the assumptions of two calculations of the neutrino flux [24, 25] are also shown. The (rather slight) consequences of the difference in slope between [24] and [25] up to $\sim 100$ GeV are discussed in [8]. The difference in normalization is a bigger effect. In the absence of all other differences in input, the rate of sub-GeV interactions of $\nu_{\mu} + \bar{\nu}_{\mu}$ would be 12% higher using the flux of Ref. [25] than with the flux used by [24]. In fact, the expected rates differ by less than 5% [1]. This accidental cancellation is a consequence of the fact that the yields of pions, and hence of muons and neutrinos, in interactions of protons with nuclei of the atmosphere are higher in Ref. [24] than in [25]. This in turn may to some extent reflect the fact that both calculations are also trying to fit the same measurements of muons [18] high in the atmosphere.

Conclusions.

- The ratio of observed to calculated sub-GeV electron-like events is 1.21, and the corresponding ratio for muon-like events is 0.74 with a calculation based on the calculation of the neutrino flux of Honda et al. [27] (analysis A of Ref. [1]). If the primary flux in that calculation were reduced to fit the recent data above 10 GeV, with no other changes being made, the excess of electron neutrinos would be increased by a similar amount (and the deficit of muon neutrinos correspondingly reduced).

- The corresponding numbers based on the neutrino flux calculation of Ref. [24] (analysis B of Ref. SK1) are essentially the same, 1.18 and 0.76. Here, however, renormalizing Ref. [24] to the lower primary spectrum measurements would have a smaller (<5%) effect because the assumed primary spectrum of protons is already fairly low.

- Note that Fig. 1 shown here differs from the figure that I showed at the
conference, which was Fig. 2 from Ref. [24]. That figure is wrong in the sense that the fit it shows for hydrogen is not the hydrogen spectrum that was actually used in the calculation of the neutrino flux. An erratum is in preparation [26]. The correct spectrum is shown as the dashed line in Fig. 1 in this paper.

- Webber [27] points out that the low normalization implied by the results of Refs. [11, 13, 14, 15] may be inconsistent with simple measurements of the integral spectrum made without spectrometers by using the local geomagnetic field to set the minimum energy.

- Several components enter into the normalization of the calculated atmospheric neutrino flux in the region of energy most important for sub-GeV events, most notably the yield of pions in collisions of protons with nitrogen and oxygen in the atmosphere and the normalization of the primary spectrum. The comparison between Ref. [24] and Ref. [25] illustrates that the two uncertainties may cancel and thus obscure the systematic uncertainties in the calculations.

- Measurements of muons high in the atmosphere provide an independent constraint that is in principle somewhat more direct [12]. The HEAT measurement of the atmospheric muon flux is somewhat lower that the MASS measurement, which has been compared to the corresponding neutrino flux calculations [24, 25].

- An independent calculation, now in preliminary stages [28], has pion yields that are somewhat lower than those used in Ref. [24].

In view of the uncertainties itemized above (and others discussed in Ref. [8]), the anomalous flavor ratios and the anomalous angular dependence observed by Super-K [3] remain the cleanest evidence for neutrino oscillations because the normalization uncertainty cancels. On the other hand, it seems unlikely that improvements or corrections to the calculation will lead to much increase in the predicted neutrino flux unless it turns out that the higher normalization of the primary spectrum is after all correct.

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Figure 1: Spectra of hydrogen (top panel), helium (middle panel) and CNO nuclei (bottom panel). Open circles show the Webber et al. data as quoted in the IMAX paper [13]. Inverted, filled triangles show LEAP; X show IMAX [13], and stars show CAPRICE [14]. Higher energy data are obtained with calorimeters. Other references are given in Ref. [24]. Dashed curves show the primary spectra of Ref. [24] and solid curves those of Ref. [25].
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