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Interaction Rates of Atmospheric Neutrinos in Nucleon Decay Dectectors

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ABSTRACT

In this talk[a] I review the steps in the calculation of atmospheric neutrinos in light of recently reported measurements of neutrino interactions in nucleon decay detectors.

1 Introduction

Reports at this conference on analysis of a total of 12.6 kT years of data by the two large water detectors show impressive agreement with each other and striking disagreement with the expected ratio of muon-like (non-showering) to electron-like (showering) events. The Kamiokande group[1] reported on 4.92 kT years of data and the IMB group[2] on 7.7 kT years. Each measures a ratio of non-showering/showering events that is only about 60% of the expected ratio. The deviation from expectation is about 4 standard deviations in each case. Several independent calculations find a ratio of $(\nu_\mu+\bar{\nu}_\mu)/(\nu_e+\bar{\nu}_e)$ in the

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GeV energy range within 5% of each other (and close to the naively expected value of 2). The absolute flux of neutrinos, on the other hand is much more uncertain.

I will address two questions in this talk: 1) Is there a ν_e/ν_μ problem? and 2) Are there too few ν_μ or too many ν_e? The answer to the first question is clearly yes, in view of the situation described in the previous paragraph. The answer to the second depends on which calculation of the neutrino fluxes is used. This ambiguity reflects an accumulation of uncertainties in the absolute normalization of the cosmic ray neutrino flux as well as in the other aspects of the calculated signal.

There are three components of the calculation of the event rate of contained interactions and the ratio of non-showering to showering events.

1. The neutrino flux.
2. The neutrino cross section.
3. The detector response.

I shall talk mostly about the first and make just a comment on the second. I have nothing to say about the third.

2 Atmospheric neutrinos

The atmospheric cascade which produces the cosmic ray neutrino beam is depicted in Eq. 1.

$$\begin{array}{lll} p \longrightarrow \pi^+ \; (+ K^+ \ldots) \rightarrow & \mu^+ + \nu_\mu & \\ & \downarrow & \\ & e^+ + \bar{\nu}_\mu + \nu_e & \\ n \longrightarrow \pi^- \; (+ K^- \ldots) \rightarrow & \mu^- + \bar{\nu}_\mu & \\ & \downarrow & \\ & e^- + \nu_\mu + \bar{\nu}_e \, . & \end{array} \tag{1}$$

Kinematics of the $\pi \rightarrow \mu \rightarrow e$ decay chain is such that the two neutrinos from muon decay each have about the same energy as the neutrino from the

Table 1: Neutrino flux calculations.

Reference	Method	Interaction model	R_ν
3. G.Barr, Gaisser & Stanev	M.C.	Parametrized data	0.48
4. Bugaev & Naumov	numerical	"	—
5. Lee & Koh	M.C.	Descendant of Ref.3	0.48
6. Honda, Kasahara *et al.*	M.C.	NUCRIN + LUND	0.46
7. Kawasaki & Mizuta	analytic	Analytic parametrization	0.49

decay of the parent charged pion. This leads to the expectation of

$$R_\nu \equiv \frac{\nu_e + \bar{\nu}_e}{\nu_\mu + \bar{\nu}_\mu} \approx \frac{1}{2} \quad \text{and} \quad \frac{\bar{\nu}_\mu}{\nu_\mu} \approx 1 \tag{2}$$

for energies low enough so that all muons decay. In addition, one expects an excess of ν_e to $\bar{\nu}_e$ because of the excess of protons to neutrons in the incident cosmic ray beam. This is because proton interactions produce an excess of fast π^+ compared to π^- and *vice versa* for neutron interactions. (Neutrons occur only in cosmic ray nuclei, whereas free protons dominate the incoming cosmic ray beam.) This naive picture is complicated by muon energy loss, muons that reach the ground and stop before decaying, muon polarization and neutrinos from kaon decay. Taking all these complications into account, the ratio is calculated[3] to be $R_\nu \approx 0.48$ in the energy range $0.1 \leq E_\nu \leq 1$ GeV. Above 1 GeV the ratio begins to decrease as muon decay in flight becomes increasingly improbable.

The numbers in Table 1 for R_ν are for Kamiokande averaged over all angles. The ratio has a significant angular dependence because of the increased probability of muon decay at large angles. For example, for $E_\nu \approx$ 1 GeV, $R_\nu(\text{hor}) \approx 0.52$ and $R_\nu(\text{vert}) \approx 0.43$ at Kamiokande. The corresponding numbers at 500 MeV neutrino energy are 0.50 and 0.46.[b] Integrating over the detector response, one might expect a $\sim 10\%$ difference between horizontal and vertical for the ratio of showering to non-showering events.

The uncertainty in R_ν can be judged by comparing results of various calculations.[3,4,5,6,7] Table 1 gives some information about the calculations,

[b]Here 'horizontal' is that half of the total solid angle with zenith angle larger than 60° above and below the horizon, and 'vertical' is the sum of the two remaining cones about the vertical. There is a very similar set of numbers for IMB.

four of which are completely independent of each other. All these calculations (except Ref. 4) include the effect of muon polarization.[8] Only the Lee & Koh calculation is three dimensional, but this appears to be unimportant for $E_\nu > 200$ MeV or so.

The calculations of Refs. 3 and 6 agree rather well in magnitude with each other over the whole energy range from 0.2 to 3 GeV, with Honda *et al.*[6] being about 10% lower than G. Barr *et al.*.[3] Around 1 GeV, the Lee & Koh result[5] is about 20% lower than G. Barr *et al.*,[3] and the Bugaev & Naumov calculation[4] is still lower, about 0.6 times the result of G. Barr *et al.*. In the case of Refs. 4 and 5, the discrepancy with Ref. 3 increases at lower energy and decreases at higher energy. Some detailed comparisons have been made between various stages of calculation and input for Refs. 3 and 6 to try to isolate sources of the relatively small difference. These will be discussed below. To summarize, there are rather large differences among the calculations of neutrino flux, but quite good agreement in the ratio of neutrino flavors, where many of the uncertainties in the calculations have cancelled.

There are three major components of the neutrino flux calculation. They are

1. Primary spectrum.
2. Production of pions and kaons.
3. Propagation and decay of charged mesons.

Of these the primary spectrum is probably the largest source of systematic uncertainty.

2.1 Primary spectrum.

The median primary energy/nucleon of the cosmic rays that generate ~GeV neutrinos is 20 GeV, and about 75 – 80% of the contribution comes from primaries with energies between 7 and 70 GeV/nucleon.[9] This is therefore the most important part of the primary spectrum for contained neutrino interactions.

In his review paper, Simpson[10] shows a compilation of data on primary spectrum that includes this energy range. This compilation[11] was used[12] as

the basis of the primary spectrum adopted[9] for our calculation[3] of neutrino fluxes. Another compilation frequently used is that of Webber & Lezniak.[13] Individual measurements can differ from each other by large amounts (in one case as much as a factor of 2 around 100 GeV). However, by drawing smooth curves joining the data, we estimated[9] that there is a $\pm 10\%$ uncertainty in normalization of the primary spectrum. Experiments[14,15] typically report $15-20\%$ systematic uncertainty in the normalization of a measurement of the spectrum. Honda et al.[6] used the spectrum summary of Webber & Lezniak[13] for their calculation of neutrino fluxes. They also performed their calculation with the spectrum used in Ref. 9 and found virtually no change (M. Honda, private communication).

Another important feature of the cosmic ray spectrum is its shape, which is normally characterized by a power law index. The uncertainty in the shape is particularly important in judging a comparison between measurements that reflect different primary energies. For example, a comparison between contained neutrino interactions ($E_\nu \sim 1$ GeV) and neutrino-induced upward muons ($\sim 10 \leq E_\nu \leq \sim 10^4$ GeV)[16] reflects the primary flux over a wide range of energies. According to the recent work of Seo et al.[14], the spectra are given by power laws in rigidity with (for differential spectrum) $\gamma = 2.74 \pm 0.02$ for protons and $\gamma = 2.68 \pm 0.03$ for helium above 10 GV. If the median energy of the primary nucleons is ~ 20 GeV for contained events and ~ 2000 GeV for upward events, there would be an uncertainty from this source of a factor of $\sim (2000/20)^{0.05} \approx 1.25$. This kind of analysis will be important for consistent interpretation of the neutrino-induced upward muons measured with the same water detectors.[17,18]

2.2 Geomagnetic cutoffs

Primary spectrum measurements are generally made at high geomagnetic latitudes to obtain the spectrum down to the lowest possible energy. The contained event rate, however, includes neutrinos from all directions, so the calculation depends on a knowledge of the geomagnetic cutoffs over the whole globe. For any particular location and arrival direction, there is a minimum magnetic rigidity that a particle must have to get down to the atmosphere and contribute to the production of secondary cosmic rays.

To illustrate the level of uncertainty that exists at present from the cutoffs, I compare the calculations of Refs. 3 and 6. Honda et al.[6] derived the cutoffs

by tracing particle trajectories through a detailed model of the geomagnetic field. We[3,9] used a calculation of cutoffs made by Cooke[19] which used the Stormer formula in an offset, inclined dipole field. The most useful way to make a comparison is to average the cutoffs over all directions. Their effect can then be expressed as a function which gives the fraction of particles of a given rigidity that contribute to production of secondaries in the atmosphere at a given site. The surviving fraction rises from 10% at $\sim$ 2 GV to 90% around $\sim$ 20 GV at the location of Kamiokande. In the crucial region around 20 GeV primary energy, the cutoffs used in Ref. 6 cut out about 10% more of the primary flux than those of Ref. 3. Below 10 GV and above 40 GV the two sets of cutoffs agree. When folded with the yields and the primary spectrum, this difference in cutoffs leads to a 5% larger neutrino flux in Ref. 3 than in Ref. 6.

2.3 Solar modulation

Low energy cosmic rays are partially excluded from the inner solar system by the expanding solar wind. This plasma process is most effective during periods of high solar activity. Solar activity varies with an eleven year cycle, and the amplitude of solar modulation is greater for lower energy particles. Cosmic rays above $\sim$ 10 GeV are relatively unaffected. The effect on the neutrino flux is most pronounced at high geomagnetic latitudes where the low energy spectrum is not cut off by the geomagnetic field. The amplitude of the modulation is about 5% for 1 GeV neutrinos at IMB but only about 1% at Kamiokande. Because the underlying effect is small, uncertainty from the treatment of solar modulation cannot contribute much to the uncertainty in the expected rate of contained events. It is interesting to ask, however, whether the effect itself can be seen in the IMB data.

2.4 Neutrino yields

The yield of neutrinos from incident nucleons of a given energy depends primarily on inclusive cross section for production of pions and kaons in collisions with air nuclei. It also depends on the propagation and decay of mesons, including muons, and on the bookkeeping scheme that tracks the cascades.

Table 2: Contained events in IMB and Kamiokande.

	KAM-II	Japan→Ohio	→ IMB threshold	IMB
e-like:	109	→ 135	→ 135	139
$\mu - like:$	103	→ 127	→ 96	97

To illustrate the uncertainty in this aspect of the calculation, we again compare with the results of Honda et al.[6] The yields of neutrinos per nucleon incident on the atmosphere are consistently about 5% higher in our calculations[3] than in those of Ref. 6 for neutrinos in the GeV energy range and for primary nucleon energies of 10 to 100 GeV. The most likely source of this difference is a difference in treatment of the inclusive cross sections.

It is worth noting that about 25% of the incident nucleons are bound in nuclei with $Z > 1$. These have been treated as free nucleons entering the atmosphere. The quantitative effect of this assumption is not known, but in conventional multiple scattering models of collisions between nuclei, it is expected to be small.[20]

3 Neutrino cross section

The flux of neutrinos and antineutrinos must be folded with the appropriate cross sections for nucleons bound in nuclei to get the event rate. Figure 1[21] shows the convolution of the neutrino flux with the charged current cross sections for neutrinos on bound (solid curves) and free nucleons (dashed curves). The energy axis is *total* energy of the charged lepton.

These yields can be used to compare the event rates of the two water detectors after accounting for the difference in thresholds. For this purpose I use the published data[1b,2a] in which each group reports on the same exposure of 3.4 kT years. The cuts are $E_e > 100$ MeV in both cases and $E_\mu > 230$ MeV ($p_\mu > 205$ MeV/c) for Kamiokande and $E_\mu > 318$ MeV ($p_\mu > 300$ MeV/c) for IMB. The numbers of events are compared in Table 2. The numbers in the third column of Table 2 estimate what the event rates in the Kamiokande detector would be at the higher geomagnetic latitude of Cleveland. The fourth column estimates the effect of shifting from the Kamiokande to the higher

IMB muon threshold (shown as the shaded region in Fig. 1.). The shifted Kamiokande numbers are in excellent agreement with the IMB numbers.

The most significant difference between the calculated neutrino fluxes in Refs. 3 and 6 is the ratio of $\bar{\nu}_e/\nu_e$, as shown in Fig. 2 from Ref. 6. (The two calculations agree for the ratio $\bar{\nu}_\mu/\nu_\mu$.) Because of the large difference of neutrino and anti-neutrino cross sections, such a difference can affect the predicted ratio of non-showering to showering events. Using the yields of Fig. 1 leads to the following conclusion: Shifting the $\bar{\nu}_e/\nu_e$ ratio from the value of Ref. 3 to the lower value of Ref. 6, while holding the $\nu_e + \bar{\nu}_e$-flux fixed, leads to a 4% increase in the predicted ratio of showering to non-showering events. This is comparable to the $\sim 5\%$ uncertainty in the ratio $(\nu_e + \bar{\nu}_e)/(\nu_\mu + \bar{\nu}_\mu)$.

4 Conclusion

The ratio of non-showering to showering events in the two large water Cherenkov detectors is significantly smaller than expected on the basis of several calculations of the ratio of muon neutrinos to electron neutrinos produced by cosmic rays in the atmosphere. Tracking calorimeter detectors[22,23] are consistent with expectation, but with lower statistical significance.

Refs. 3, 5 and 6 used essentially the same primary spectra. The differences among them (at the level of $\pm 10\%$) therefore indicate the present level of uncertainty from the cutoffs and evaluation of the atmospheric cascade. To this must be added the systematic uncertainty in the primary spectrum itself, which is ± 15 or 20% for individual experiments[14,15], and so at least $\pm 10\%$ when different experiments are combined. Given these uncertainties in the absolute normalization of the calculations, it is not possible at present to say whether there are too few detected muon-like events or too many electron-like events. Clearly this information is crucial for any interpretation in terms of neutrino oscillations or extraterrestrial neutrinos.

Study of neutrino-induced upward muon measurements[17,18] should be helpful. Comparison with measurements of related secondary fluxes, e.g. muons[24,25] and electrons[26] especially at high altitude, may make it possible to reduce the uncertainty in the atmospheric neutrino fluxes significantly, because these secondaries reflect much of the same cascade physics, as well as the same primary spectrum, as the neutrinos. New measurements of muon and electron fluxes at high altitude may be desirable for this purpose.[27]

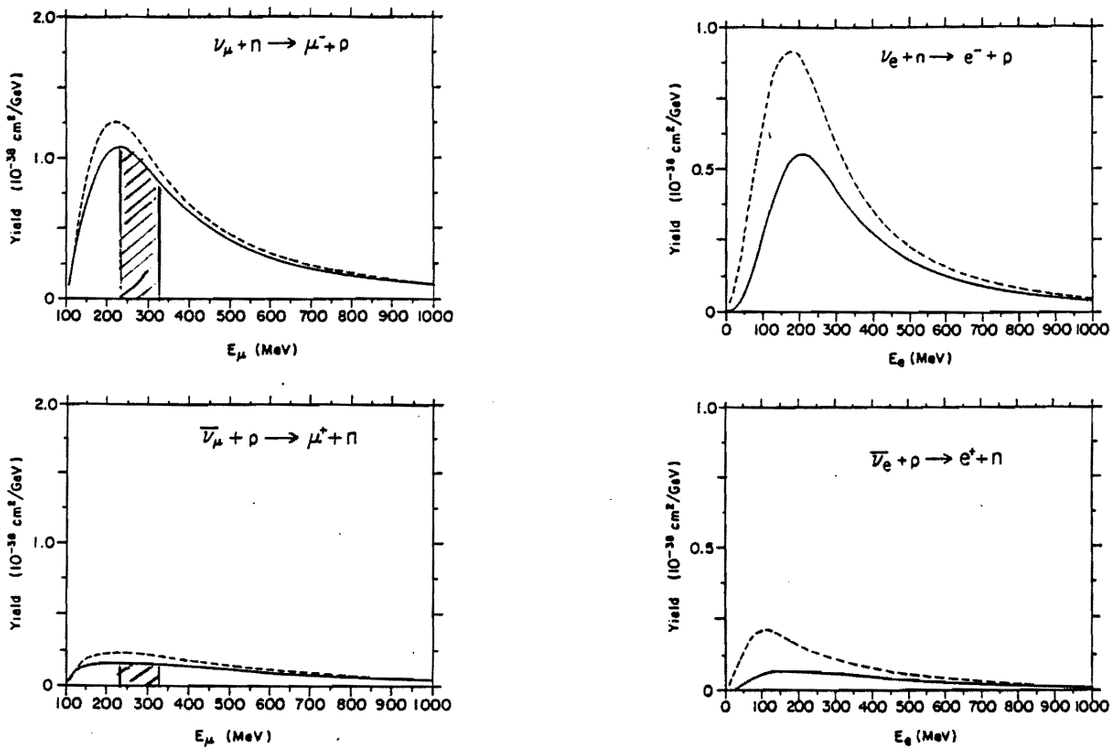

Figure 1: Differential lepton yield integrated over atmospheric neutrino spectrum. Dashed: free nucleons; Solid: bound nucleons. (From Ref. 21.)

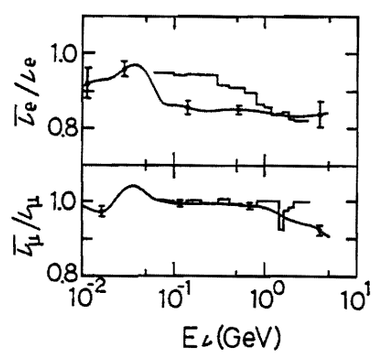

Figure 2: Calculated antineutrino/neutrino ratios. Histogram: Ref. 3; Solid line: Ref. 6. (From Ref. 6.)

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