Pion Production in Proton Collisions With Light Nuclei: Implications for Atmospheric Neutrinos

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Abstract

Differences among calculations of the atmospheric neutrino beam can be traced in large part to differences in the representation of pion production by protons interacting with nuclei in the atmosphere. In this paper we review the existing data with the goal of determining the regions of phase space in which new measurements could help to improve the input to the calculations.

1 Introduction

The observed up-down asymmetry of the flux of muon-like events induced by interactions of atmospheric neutrinos has been interpreted as evidence for neutrino oscillations [1]. The case for neutrino oscillations is especially strong for the multi-GeV events at Super-Kamiokande because the energies are high enough so that the charged leptons follow the neutrino direction closely and expose the oscillation effects as a function of the neutrino pathlength. On the other hand, comparisons to calculations of the atmospheric neutrino flux over as broad an energy range as possible are essential for making a detailed interpretation of the data and generally for giving confidence in the basic
result. In addition, calculations play a crucial role in comparison of measurements made at different locations and with different techniques. In particular, the Soudan experiment [2], and IMB [3] previously, detect neutrino interactions in a range similar to Super-Kamiokande (and Kamiokande [4]), but the geomagnetic environments are quite different, which changes the neutrino angular distribution expected in the absence of oscillations. Measurements of neutrino-induced upward muons, as also at MACRO [5], are also sensitive to oscillations, but in a different energy regime (see Fig. 1).

![Figure 1: Distributions of neutrino energies that give rise to four classes of events. Sub-GeV and multi-GeV refer to the two classes of contained events at Superkamiokande. The response for contained events is averaged over all angles, while for stopping and throughgoing muons it is only given for vertical upward going neutrino induced muons.](image)

There are several independent calculations of the flux of atmospheric neutrinos [6–11]. In all cases but one [9], the calculations start with the primary cosmic-ray spectrum as measured (protons and alpha-particles give
the dominant contributions) and simulate the resulting cosmic-ray cascade in the atmosphere, calculating the fluxes of $\nu_e$, $\bar{\nu}_e$, $\nu_\mu$, $\bar{\nu}_\mu$, $\mu^+$, and $\mu^-$. The calculated muon fluxes can be compared with measurements of muons at high altitude [12–16] as a check of the calculation. Perkins [9] starts from the measured muon flux and uses the kinematic relationship between muons and neutrinos to derive the neutrino flux. A limitation of the muon fluxes is that the individual measurements generally have low statistics and depend more sensitively than the neutrinos on the details of geomagnetic and three-dimensional effects.

The most recent calculations [10, 11] constitute a very significant technical advance in that they are three-dimensional. In previous calculations secondary particles had been assumed to follow the direction of the primary cosmic-ray that generated them. A major conclusion of Ref. [10] is that for practical purposes the one-dimensional calculations give adequate results. This is because Fermi-momentum of the target nucleons of the neutrino interactions, compounded by limited angular resolution, smear out angular features visible in fluxes of $\sim$GeV neutrinos. A corollary of this conclusion is that simpler one-dimensional calculations can be used for comparison of calculations in order to trace sources of differences among the calculated neutrino fluxes.

Some time ago the existing one-dimensional calculations were compared [17]. The dominant sources of difference were found to be the assumed primary spectrum and the representation of pion production in collisions of protons with light nuclei. Although differences in input were at the level of 20-30% – or larger in some cases – the neutrino fluxes of the two calculations [18, 19] that have been used extensively for input to the detector simulations differ by much less. This is a consequence of compensating uncertainties together with the fact that both calculations were constrained to fit the same (ground-level) muon data. Recently, several new measurements of the primary spectrum [20–22] confirm the lower [23] of two older measurements [23, 24], leaving differences in representation of pion production as the major source of uncertainty for GeV neutrino fluxes.

A striking example is the difference between the calculations of Battistoni et al. [10] and the Bartol fluxes [6]. This comparison, which was made [25] using the one-dimensional version of Ref. [10] and the same assumed primary spectrum as Ref. [6], gives neutrino fluxes 20-30% lower than Ref. [6] for $E_\nu < 10$ GeV. A detailed comparison with the new calculation of Ref. [10] is currently in progress [26].
2 Inclusive pion production around 20 GeV

To see what range of interaction energies is most important for the various classes of events shown in Fig. 1, one needs to look at the distributions of primary energies that produce the events. Roughly speaking, for the steep cosmic ray spectrum the most relevant primary energies are an order of magnitude higher than the neutrino energy of interest. For the upward neutrino-induced muons, for example, the important range of interaction energies extends up to several TeV. In this energy range, the uncertainties in the primary spectrum are still relatively large, and there are also significant uncertainties from the amount and momentum distribution of kaon production [28], which will be addressed in [26]. Here we concentrate on the lower energy events (e.g. the sub-GeV events at Super-Kamiokande) for which most of the contribution comes from interactions of primary cosmic-ray nucleons with energies between 10 and 100 GeV. A similar range of energies is responsible for the Soudan events and for contained events in IMB and Kamiokande.

We show the distribution of primary energies that gives rise to the sub-GeV events at Super-Kamiokande in Fig. 2 [27]. We show separately the response for downward (C) and upward (B) events, as well as the response that would apply if there were no geomagnetic field (A). It is interesting to note that the geomagnetic cutoff leads to an observable site-dependence of the ratio of downward to upward moving events. In the absence of oscillations, due to the higher local geomagnetic cutoff at Kamioka in contrast to the very low vertical cutoff in the northern U.S., the ratio of downward to upward going leptons is respectively less and greater than one.

One of the most extensive data sets in the energy range responsible for sub-GeV events is the work of Eichten et al. [29]. Figure 3 shows the data from this experiment for production of $\pi^+$ from interactions of 24 GeV/c protons on beryllium. The solid lines are fits of the form

$$2E \frac{dN}{dpd^2p_T} = a(p) \times \exp \{ -b(p) m_T \} , \quad (1)$$

where the transverse mass is defined as

$$m_T = \sqrt{p_T^2 + m_{\pi}^2} , \quad (2)$$

and $a(p), b(p)$ are free parameters at each value of pion momentum $p$. This form gives good fits for all momenta except the lowest two values. The dashed
Figure 2: Response for sub-GeV muon-like events in Super-K to the energy of the primary cosmic ray nucleons. A: no geomagnetic cutoff; B: events from lower hemisphere (upward going leptons); C: events from upper hemisphere (downward going leptons). Each pair of curves shows the range of the signal between minimum (solid) and maximum (dotted) of solar activity.

lines show fits in which the pion mass entering Eq. (2) is also treated as a free parameter. For negative pions, the form (1) gives good fits for all measured momenta.

What is important for the overall normalization of the atmospheric neutrino flux is the total yield of pions integrated over all phase space. This involves both interpolation and extrapolation. Figure 4 illustrates the fraction of the pion production cross section that requires interpolation only for the data of Ref. [29]. The curve represents the fraction of secondary pions falling into the acceptance range of the experiment as function of $x_{\text{lab}} = p/p_{\text{beam}}$. 


Figure 3: Data on inclusive $\pi^+$ production in proton-beryllium collisions at 24 GeV [29]. The solid lines correspond to fits using the pion mass in (2) and the dashed curves show the result if the mass is treated as free parameter.

Thus, for example, for $\pi^+$ at $p =$ 6 GeV ($x_{\text{lab}} \approx 0.25$) approximately 75% of the integral over transverse momentum does not require extrapolation into unmeasured regions of transverse momentum. Most important is the fact that in this experiment there are no data at all for $p < 4$ GeV. In this
Figure 4: Fraction of pion production cross section covered by the data of Eichten et al. (p-Be at 24 GeV [29]), Allaby et al. (p-Be at 19.2 GeV [32]), and Abbott et al. (p-Be at 14.6 GeV [33]). For Eichten et al. the upper and lower curves show the coverage for $\pi^+$ and $\pi^-$ respectively. The other experiments have acceptances which are essentially identical for negatively and positively charged pions.

region, therefore, the representation of pion production depends on how well the model extrapolates in both longitudinal and transverse momentum.

Other experiments [31–33] cover various regions of phase space at various nearby beam energies (see Fig. 4). The Lundy et al. data set [31] (p-Be at 12.5 GeV) is not shown since it corresponds to pion production spectra which are not consistent with the other measurements.

Only the data of Abbott et al. [33] reach into the $x_{\text{lab}}$ region of about 0.1 to 0.2, which is an important contributor to the atmospheric lepton fluxes. Since these measurements are published as function of particle rapidity $y = \log[(E + p_L)/(E - p_L)]$ and transverse mass $m_T$, the conversion of the data into $dN/dx_{\text{lab}}$ requires a two-dimensional inter- and extrapolation resulting in substantial uncertainties.
In Fig. 5 we show the inclusive pion spectra obtained by integrating analytic parametrizations fitted to the data of Eichten et al. [29], Allaby et al. [32] and Abbott et al. [33]. The sensitivity of the results to different parametrizations used for extrapolation is indicated by showing two points at the same $x$-value for a given data set. In addition to the typical systematic uncertainties of these experiments of about 15%, different methods of extrapolation result in pion spectra which are different by up to 25%.

Finally, there are many proton-beryllium and proton-carbon particle production measurements published which are restricted to one or two angular bins of the secondaries (for example, Baker et al. [34], 10, 20, 30 GeV; Dekkers et al. [35], 19, 23 GeV). Due to the lack of theoretical understanding of soft hadronic particle production these data sets cannot be used for inter- and extrapolation to obtain secondary pion spectra.

3 Pion production other energies

There are several measurements at lower energy, which cover some relevant regions of phase space [36–47]. In most of the cases only $\pi^-$ distributions
have been measured and some of the papers report on mean multiplicities or multiplicity distributions only. Also, many data sets refer to thick targets and are not directly usable for cascade calculations. In the following we discuss only some of the published data sets where final state particles have been identified and a large fraction of the phase space was covered by the experiment. In particular, we do not consider the numerous emulsion measurements.

At low energy, the data of \[39–41\] are interesting because of the full coverage of the phase space. For example, in Fig. 6 we show $\pi^-$ production spectra for proton-carbon collisions at 4.2 and 10 GeV. The mean $\pi^-$ multiplicities are respectively 0.33 ± 0.02 and 1.00 ± 0.03 \[39, 41\]. In addition, in Refs. \[39, 40\] data on $\alpha$-carbon and carbon-carbon collisions with 4.2 GeV/nucleon are given.

The most relevant data sets at higher energy known to the authors are in Refs. \[48–50\]. Ref. \[48\] gives the ratio of particle production yields in proton-beryllium and proton-aluminum collisions at 67 GeV. Such studies are important for the extrapolation of p-Be data to p-air collisions. Whereas the

\[\text{Figure 6: Inclusive production spectrum of negative pions in proton-carbon collisions [39, 41].}\]

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\[\text{In Ref. [40] the 4.2 GeV data are also given as double-differential distributions } Ed^3\sigma/dp^3 \text{ in 10 degree bins of the azimuthal angle.}\]
measurements published in Ref. [48] refer to thin targets, the data of Ref. [51] are for thick targets and both thick and thin targets are considered in Ref. [49]. The measurements of p-Be collisions at 450 GeV of the NA56/SPY collaboration [50] cover the important transverse momentum range of 0 – 600 MeV, however cross sections obtained by extrapolation to a thin Be target are given only for the very forward direction.

4 Conclusion

After the new measurements of the primary cosmic ray spectrum, the uncertainties in the calculated sub-GeV neutrino fluxes are dominated by the limited information and understanding of hadronic interactions in the energy range from about 5 to 100 GeV.

Most pressing is the need for a single experiment that covers pion production at several beam energies in the peak region of the sub-GeV events in Fig. 2, namely, around 20 GeV/c. Targets should be as close as possible to the constituents of the atmosphere, especially nitrogen. If this is not possible, a series of targets with mass number spanning A=14 should be done.

At low energy, several data sets cover $\pi^-$ production. Data on $\pi^+$ production is very sparse and many experiments refer to thick targets or suffer from low statistics. Thus, a consistent set of new measurements extending to lower energy would also be important, especially for interpreting measurements made at low geomagnetic cutoff.

Use of a beam of helium nuclei would also be of interest. In the energy range from 10 to 100 GeV/nucleon, approximately 80% of the primary cosmic-ray nucleons are free protons and 15% are bound in alpha particles. Only 5% or less are in heavier nuclei.

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