Proceedings of ICRC 2001: 1381 © Copernicus Gesellschaft 2001

ICRC 2001

Hadronic interactions for atmospheric cascades

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Abstract. We review data on pion and kaon production as it relates to atmospheric cascades. The event generator TARGET has been revised accordingly. We illustrate its use by repeating the one-dimensional calculation of the atmospheric neutrino flux (Agrawal *et al.*, 1996). We will discuss the extent to which improvements in representation of pion and kaon production lead to differences in the resulting fluxes of atmospheric neutrinos.

1 Introduction

Interest in neutrinos and muons generated by cosmic-ray interactions in the atmosphere has intensified in light of the discovery by the Super-Kamiokande collaboration (Fukuda *et al.*, 1998) of evidence for neutrino oscillations in their data on atmospheric neutrinos. Two independent flux calculations (Honda *et al.*, 1995; Agrawal *et al.*, 1996) have been widely used for interpretation of measurements of atmospheric neutrinos. More recently, new, three-dimensional calculations have been made (Battistoni *et al.*, 2000; Honda *et al.*, 2001), which remove the major technical approximation of the original calculations. Differences among the calculations are at the level of 20% in overall magnitude and 5% or less in the ratios of ν_e/ν_μ and $\bar{\nu}/\nu$. Although there are significant differences between the 3D and 1D calculations (Lipari, 2000a), especially in the angular distributions of sub-GeV neutrinos near the horizon (Lipari, 2000b), the major differences are due rather to differences in the treatment of pion production and in the primary spectrum used (Battistoni *et al.*, 2000; Honda *et al.*, 2001).

New measurements of the primary spectra of protons and helium up to 100 GeV (Sanuki *et al.*, 2000; Alcaraz *et al.*, 2000) have now reduced this source of uncertainty significantly, so that the major remaining uncertainty is in the treatment of pion production in the various calculations. In this paper we present an initial report on a survey of accelerator data and its implications for treatment of hadronic interactions. This is a preliminary step toward a full three-dimensional calculation and toward a detailed assessment of remaining uncertainties in the calculated spectra of atmospheric neutrinos in the absence of oscillations.

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We have identified two or three particular features of the event generator (TARGET) used in our previous calculation (Agrawal *et al.*, 1996) that needed to be adjusted to obtain better agreement with data, including in particular some that were not available when TARGET was initially prepared (Gaisser, Protheroe & Stanev, 1983). The new TARGET is fully three-dimensional, but here we integrate over the transverse dimensions. We compare old and new versions of TARGET with each other and with data. We also illustrate the differences in neutrino fluxes that follow from the different treatments of hadronic interactions, and we compare to the neutrino fluxes on the web page Battistoni *et al.* (2001) associated with the work of Battistoni *et al.* (2000). More detailed comparisons among various representations of hadronic interactions and the corresponding neutrino fluxes will be made in a future paper in collaboration with the authors of Battistoni *et al.* (2000) and Honda *et al.* (1995). All the comparisons in this paper are made using the same primary spectrum and the same treatment of geomagnetic cutoffs as in Agrawal *et al.* (1996). The same primary spectrum is used by Battistoni *et al.* (2000).

2 Treatment of hadronic interactions

TARGET is a simple event generator for hadronic interactions that can be plugged into any cascade program. It is primarily designed to treat collisions of single hadrons with nitrogen and oxygen nuclei for use in calculation of atmospheric cascades. For comparison we use primarily data with beryllium targets.

As always, our approach remains to fit the data with a parametric form that represents the dependence on transverse and longitudinal phase space, as described recently by Engel, Gaisser & Stanev (2000). We then integrate over trans-

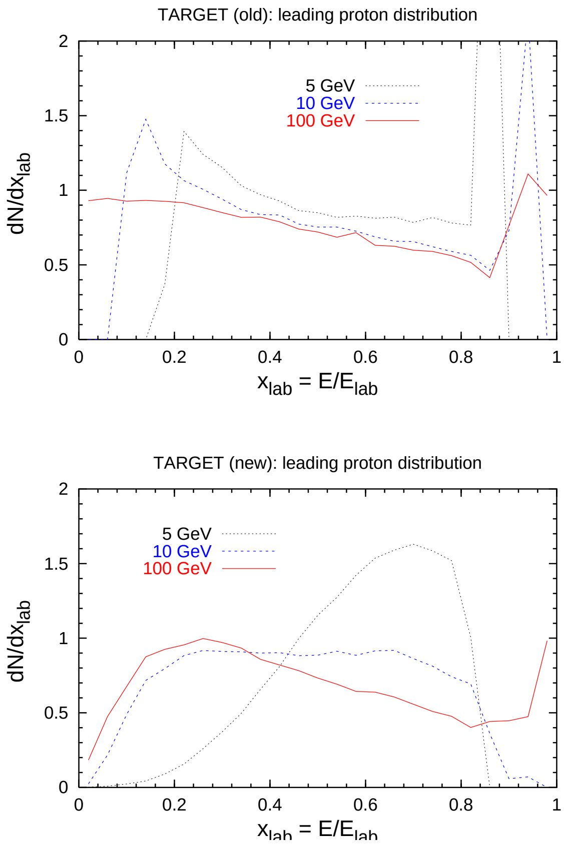

Fig. 1. Comparison of the proton distributions in its original version Gaisser, Protheroe & Stanev (1983) (upper panel) with the improved version.

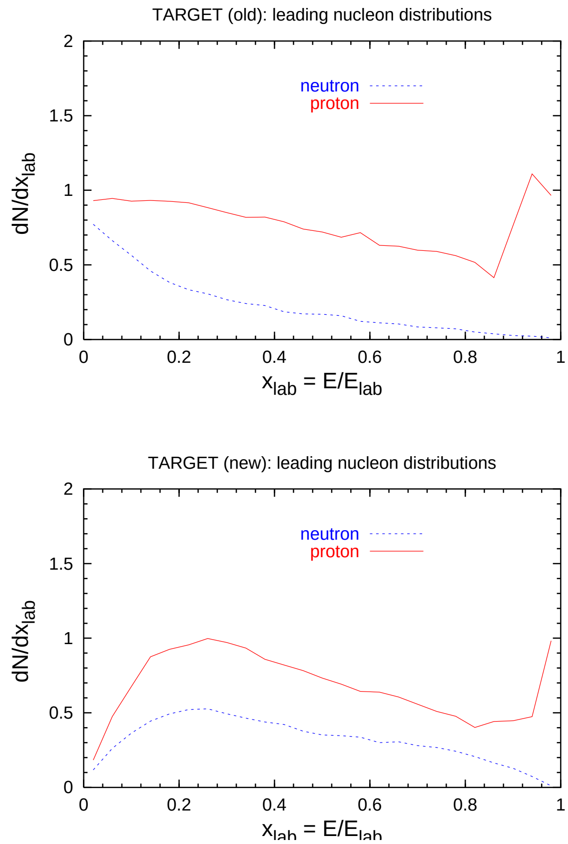

Fig. 2. Comparison of the proton (solid) and neutron (dashed) distributions for original (upper panel) and improved (lower panel) versions of TARGET.

verse momentum and adjust the resulting one-dimensional distributions so that the sum of all inclusive cross sections conserves energy. Individual interactions are generated from these distributions conserving energy on an event-by-event basis. Although TARGET handles interactions generated by nucleons, pions and kaons, we confine our discussion in this paper to interactions generated by nucleons since these interactions are by far the main source of the sub-GeV and multi-GeV samples at Super-Kamiokande. All types of interactions are included in the calculation of the neutrino flux.

The treatment of many features of hadronic interactions remain quite simple in the new version of TARGET. This is intentional. We believe there is merit in having a simplified approach in which it is easy to identify the main properties of the interaction model (such as how the beam energy is divided among the secondaries) and to follow the consequences for production of secondaries in the atmosphere. Our approach is complementary to use of more realistic, and therefore more complex, treatments such as the very complete FLUKA code (Fasso *et al.*, 2001).

2.1 Leading nucleons

Each time it is called, the event generator first selects a single nucleon, which is the product of the fragmentation of the incident nucleon. Neither nucleons from the target (although their energy is subtracted from the energy available for pion production) nor production of $N\bar{N}$ pairs are considered in TARGET. The first decision is whether or not the interaction is diffractive (target dissociation only is considered). If not, the next decision is whether or not a hyperon is produced. If so its momentum and decay to $N\pi$ are treated, and an accompanying kaon of the appropriate sign is produced. Otherwise the leading nucleon is chosen directly, either as a neutron or a proton, each from its own distribution.

In Fig. 1 we compare the proton distributions in old and new versions of TARGET. The new version has two main improvements. First, diffraction turns on gradually with energy. Second, the momentum distribution of the protons changes gradually from a fireball type distribution at low energy to a longitudinal phase space distribution asymptotically.

An equally important change in the nucleons is the treatment of neutrons. Previously, based on some early data on neutron production Whalley *et al.* (1979), the neutron distri-

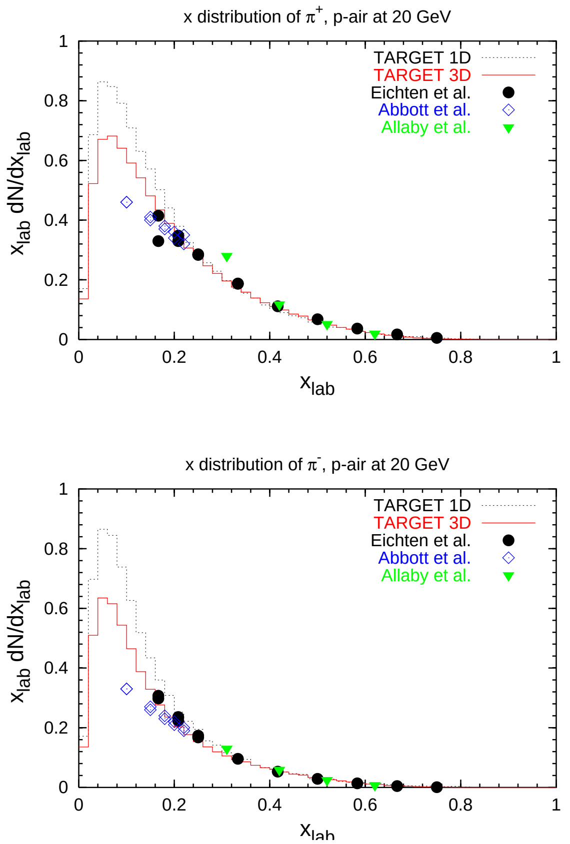

Fig. 3. Comparison of pion distributions with data of Refs. Eichten *et al.* (1972); Allaby *et al.* (1970); Abbott *et al.* (1992).

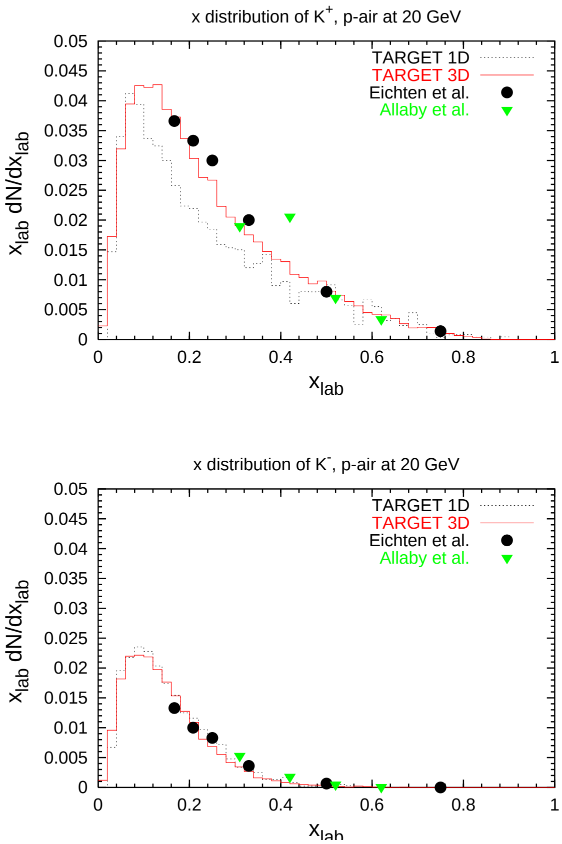

Fig. 4. Comparison of kaon distributions with data of Refs. Eichten *et al.* (1972); Allaby *et al.* (1970).

bution had a different shape from the proton distribution, and, in addition, the n/p ratio was quite low ($< 1/3$). Now, motivated by simple quark model considerations, as well as preliminary data from the NA49 experiment NA49 (2001), the directly chosen (i.e. non-diffractive, non-hyperon) $n/p = 1/2$. Fig. 2 compares neutron and proton distributions in the original and improved versions of the program.

2.2 Pion and kaon production

Largely as a consequence of the changes in the treatment of the leading nucleon described above, the pion distribution in the new version of target is in better agreement with data than previously. This is illustrated in Fig. 3. The nucleon distribution is slightly more elastic, with a smaller probability of extremely inelastic interactions, which leads to somewhat less pion production.

A potentially important change for neutrino fluxes is the increase in the π^+/π^- ratio associated with the increase in the n/p ratio. Such a change is supported by measurements of the pion charge ratio in pp collisions. Atmospheric nuclei have equal numbers of neutrons and protons, so we compare to $(\pi^+ - \pi^-)/2$ when looking at multiplicity data from pp collisions (Antinucci *et al.*, 1973; Tan & Ng, 1983).

The principal change for kaons is the increase in production of K^+ associated with a corresponding increase in hyperon production to obtain better agreement with measurements (Eichten *et al.*, 1972; Tan & Ng, 1983).

3 Neutrino fluxes

Although the new version (TARGET2.1) is designed for three-dimensional calculations, as an initial test, we repeat the one-dimensional calculation of Agrawal *et al.* (1996). We show in Fig. 5 the neutrino fluxes at Kamioka averaged over all directions. The treatment of geomagnetic cutoffs and the primary spectrum are identical to ones in Agrawal *et al.* (1996). In particular, we use the superposition approximation, treating separately three groups of incident nucleons: free protons, protons bound in nuclei and incident neutrons. Cutoffs are applied in rigidity, assuming equal numbers of bound protons and neutrons arrive in nuclei (mostly helium). The corresponding fluxes for Soudan are shown in Fig. 6. We display the results as $dN_\nu/d\ln(E_\nu)$ multiplied by one power of E_ν and summing $\nu + \bar{\nu}/3$ to give an approximately accurate graphical impression of the distributions of neutrino interactions, as they reflect the neutrino cross sections. For

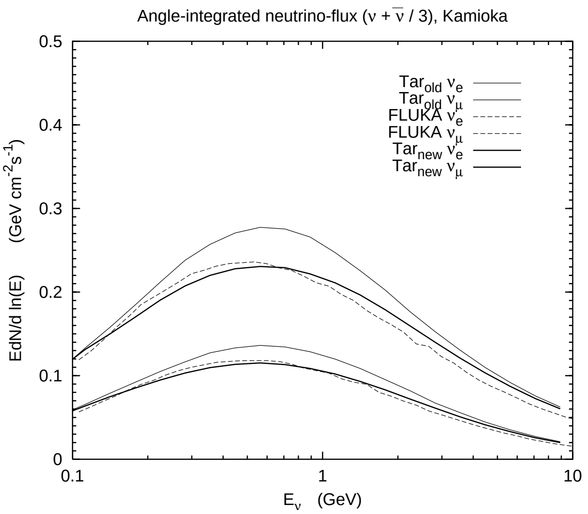

Fig. 5. Angle-integrated neutrino fluxes at Kamioka: old and new versions of TARGET compared to FLUKA Battistoni *et al.* (2001).

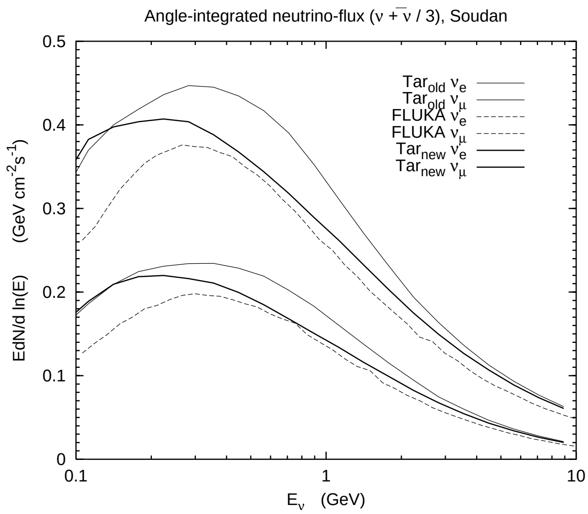

Fig. 6. Angle-integrated neutrino fluxes at Soudan: old and new versions of TARGET compared to FLUKA Battistoni *et al.* (2001).

$E_\nu < 1$ GeV the cross-section weighted ratio of electron to muon neutrinos is 1–2% larger in the new version of TARGET than in the old, while for $E_\nu > 1$GeV it is lower by a similar amount.

In view of the change in the charge ratio of pions, it is also of interest to compare the ratios of neutrinos and antineutrinos among the various calculations. Because of the difference in cross section between neutrinos and antineutrinos, this could be important. The ratio $\nu_\mu/\bar{\nu}_\mu$ remains near unity in the sub-GeV range of E_ν in both new and old versions of TARGET, but increases by ≈ 3% more in the new version than the old in the few GeV range. The $\nu_e/\bar{\nu}_e$ ratio is about 5% higher in the new version from 0.1 to 10 GeV.

4 Conclusion

In this paper we have concentrated on the energy range from several GeV to ~ 100 GeV that is most important for production of the sub-GeV and multi-GeV events in water Cherenkov detectors and at Soudan. Tuning the TARGET event generator to produce distributions of nucleons that are in better agreement with physical expectations leads to better agreement with data on pion production. We have tested the new event generator by repeating the one-dimensional calculation of Agrawal *et al.* (1996), keeping all details of the calculation the same except for substitution of the new version of TARGET for the original. The angle averaged flux of neutrinos at Super-K now agrees rather well with the result of Battistoni *et al.* (2000, 2001) over the whole energy range from 0.1 to 10 GeV. For Soudan, our angle-averaged result remains significantly higher for $E_\nu < 0.4$ GeV reflecting differences in the treatment of the interaction of very low energy primary nucleons. A more detailed comparison of current calculations of fluxes of atmospheric neutrinos will be made in cooperation with the authors of (Honda *et al.*, 1995) and (Battistoni *et al.*, 2000).

Acknowledgements. We are grateful for extensive discussions with Giuseppe Battistoni, Motohiko Honda and Alfredo Ferrari. This research is supported in part by the U.S. Department of Energy under DE-FG02 91ER 40626.

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