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Primary spectrum to 1 TeV and beyond

T. K. Gaisser[1]**, M. Honda**[2]**, P. Lipari**[3]**, and T. Stanev**[1]

[1]Bartol Research Institute, Univ. of Delaware, Newark, DE 19716, USA
[2]Institute for Cosmic Ray Research, University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa City, Chiba 277-8582, JAPAN
[3]Dipt. di Fisica and INFN, Università di Roma I, 00185, Roma, ITALY

Abstract. We describe fits to recent measurements of the primary proton and helium spectra in the energy region below 100 GeV. Including also the contribution of heavy nuclei, we discuss remaining uncertainties involved in the extrapolation to the TeV energy range and beyond, which is essential for calculation of fluxes of atmospheric muons and neutrinos. We also discuss implications of the recent measurements for the interstellar spectrum in the GeV region.

1 Introduction

Accumulating evidence for neutrino oscillations based on observations of atmospheric neutrinos has intensified interest in a detailed understanding of cosmic-ray induced neutrinos and muons. Calculations of the fluxes of atmospheric muons and neutrinos start with the primary spectrum outside the atmosphere. Uncertainties in the measurements of the primary spectra of protons, helium and heavier nuclei therefore affect, to a greater or lesser degree, the precision with which the secondary fluxes may be calculated. Other sources of uncertainty, including treatment of pion production and bending of charged particles in the geomagnetic field are also important. In this paper we consider only the primary spectra.

New measurements of the primary spectra of protons and helium by a series of balloon flights of magnetic spectrometers, beginning with LEAP (Seo *et al.*, 1991) and continuing with MASS (Bellotti *et al.*, 1999), IMAX (Menn *et al.*, 2000), CAPRICE (Boezio *et al.*, 1999), and BESS (Sanuki *et al.*, 2000), and the extended AMS flight on the Space Shuttle (Alcaraz *et al.*, 2000a,b), have reduced significantly the uncertainties in the primary spectrum up to 100 GeV compared to what was previously known. The primary spectra are less well known at higher energy. At low energy, especially below 10 GeV, solar modulation becomes important and introduces an additional source of uncertainty.

Our goal is to propose a best-fit primary spectrum and eventually to specify the uncertainties that remain at present and how they propagate through to uncertainties in the expected fluxes of muons and of neutrinos in the absence of oscillations. In this paper we propose a standard primary spectrum of nucleons, make a preliminary analysis and outline the steps that need further work.

2 Fits to data

Before discussing fits to the measurements of various components of the primary cosmic rays, it is helpful for orientation to anticipate our results and to show the fractional contribution of different groups of primaries to the flux of nucleons per GeV per nucleon. This is shown in Fig. 1 as a function of kinetic energy per nucleon. What is plotted is the fractional contribution of each group of nuclei to the spectrum of nucleons. So, for example, a ^4He nucleus with a total energy of 60 GeV contributes 4 nucleons at 15 GeV/nucleon. Since it is energy per nucleon that matters for uncorrelated particle production, this is the most appropriate way to display the composition in relation to calculations of fluxes of atmospheric muons and neutrinos. Nuclei heavier than helium contribute $\sim$ 10% or less at all energies. They are shown here in the conventional groups used in the TeV region and above. We will discuss later the extrapolation of our fits to high energy for comparison to air shower measurements of the all-particle spectrum.

We have used two forms to fit a differential spectrum in kinetic energy per nucleon (E_k) to the data on the various mass groups:

$$\phi(E_k) \;=\; K \times \left(E_k + b\,\exp\left[-c\sqrt{E_k}\right]\right)^{-\alpha} \tag{1}$$

and

$$\phi(E_k) \;=\; K \times (E_k \,+\, m_p)^{-\alpha} \times \exp\left[\frac{-c}{\epsilon \,+\, p}\right], \tag{2}$$

where p is momentum per nucleon, $\epsilon = 0.25$ GeV is a constant and all energy units are expressed in GeV. Values of the

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Correspondence to: T. K. Gaisser (gaisser@bartol.udel.edu)

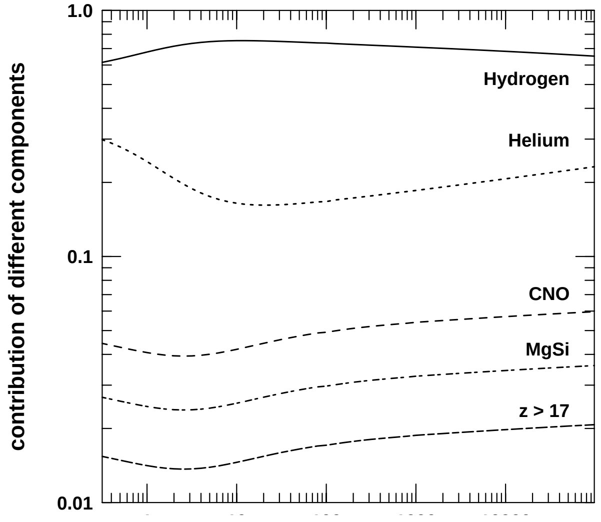

Fig. 1. Contribution of five mass groups to the flux of nucleons as a function of kinetic energy per nucleon (GeV/A).

parameters in the fits of Eq. 1 are given in Table 1. Here (unlike Fig. 1) the normalization is to particles (e.g. number of helium nuclei per GeV/nucleon, etc.).

Table 1. Fit parameters for all five components in the fit of Eq. 1.

Eq. 1	α	K	b	c
Hydrogen	2.74±0.01	14900±600	2.15	0.21
He (high)	2.64±0.01	600±30	1.25	0.14
He (low)	2.74±0.03	750±100	1.50	0.30
$z > 2$ (high)	2.70	95.5	1.78	0.02
$z > 2$ (low)	” ”	82.2	” ”	” ”

2.1 Protons

This is the most extensive data set. The recent measurements we refer to have been taken at various points in the solar cycle, except at solar maximum. Differences in normalization range from $< 5\%$ to $\sim 25\%$. Measurements of BESS98 (Sanuki *et al.*, 2000) and AMS (Alcaraz *et al.*, 2000a) were taken at times of nearly identical solar modulation, and they agree with each other to within 5%. We use these two data sets for our fits. Figure 2 compares the fits of Eqs. 1 and 2 to these data. Also shown are various measurements of the proton spectrum at higher energy. The higher energy data are not used in the fits. The lines shown are extrapolations of the fits to the BESS98 and AMS data.

In the energy range from 0.2 to 2 TeV, which is responsible for about half the upward, throughgoing muons, the only experiment is that of Ryan *et al.* (1972), which measured the proton spectrum above 50 GeV with a balloon-borne calorimeter. In the region of overlap with Sanuki *et al.* (2000) and Alcaraz *et al.* (2000a), the Ryan *et al.* data are about 25% higher than the magnetic spectrometer measurements. Since the calorimetric energy determination is likely subject to larger systematic errors, we assume it should be renormalized downward to the spectrometer data.

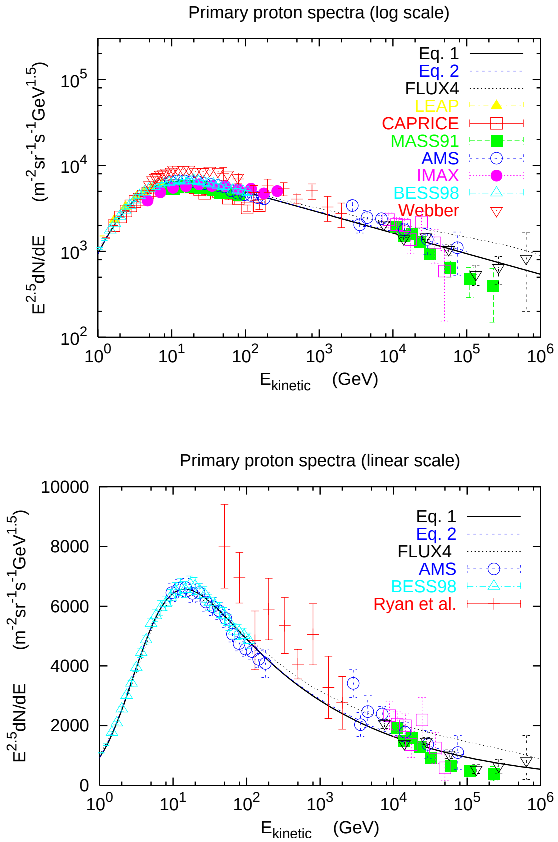

Fig. 2. Differential flux of protons compared to fits of Eqs. 1 and 2, which are nearly indistinguishable on these plots. Also plotted is the proton spectrum of Agrawal *et al.* (1996). References for the high-energy points are given in Gaisser (2001).

2.2 Helium

For helium we again use the BESS98 (Sanuki *et al.*, 2000) and AMS (Alcaraz *et al.*, 2000b) data. Here, however, the difference between the two experiments is more significant than for protons. BESS presents data as a function of kinetic energy per nucleon, whereas the AMS results are tabulated in terms of rigidity. The difference is larger than it appears in the graph in Alcaraz *et al.* (2000b). This is because a contribution of 15% ^{3}He is assumed by AMS in converting their measured rigidity spectrum to kinetic energy per nucleon, whereas (Sanuki, private communication) BESS assumed 100% ^{4}He. When the two data sets are compared with uniform assumptions for the helium isotope ratio, the AMS normalization appears to be some 10% lower than BESS.

Using Eq. 1 we make a high and a low fit to the helium data summarized in Fig. 3. The “high” fit uses all data except AMS, while the “low” fit uses only AMS and BESS data. Because of the smaller error bars on the AMS data the “low” fit is drawn to the AMS data and has a steeper spectrum.

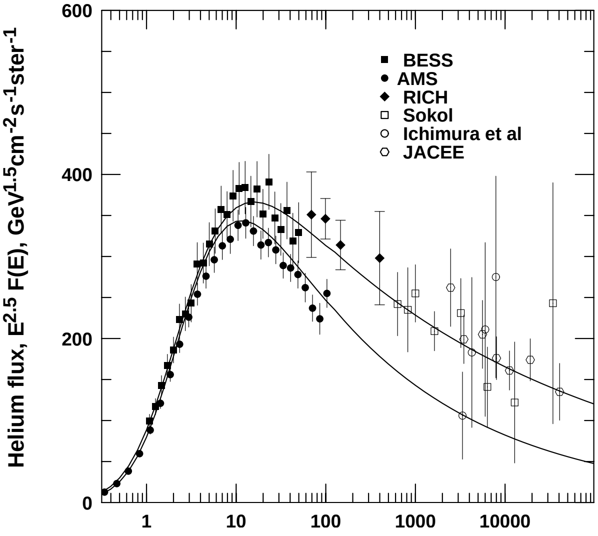

Fig. 3. Differential flux of helium compared to the 'high' and 'low' fits of Eq. 1 in units of $m^{-2}sr^{-1}s^{-1}(GeV/A)^{1.5}$.

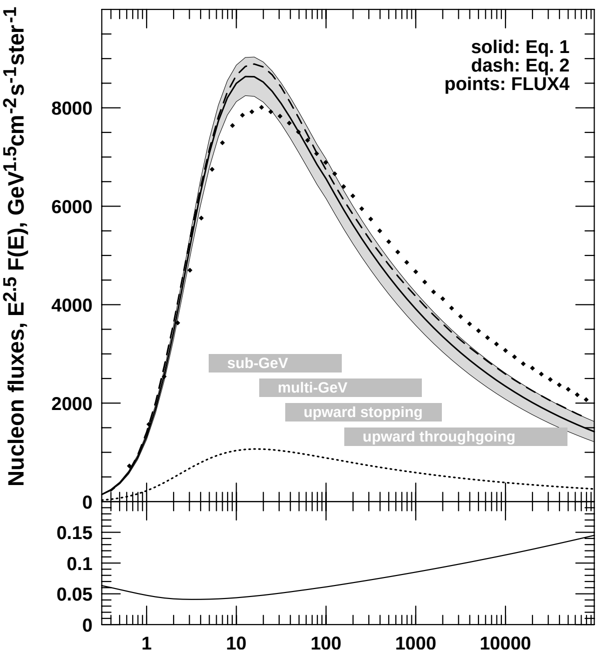

Fig. 4. Differential flux of nucleons in units of $m^{-2}sr^{-1}s^{-1}(GeV)^{1.5}$, with neutrons shown separately (dotted line). The points labeled 'FLUX4' show the all-nucleon spectrum used in Agrawal *et al.* (1996). The dashed line shows the fit of Eq. 2. The bands indicate the energy ranges that contribute 90% of the rates for the four types of events at Kamioka. The lower panel shows the half-width of the error band as a fraction.

2.3 Heavy nuclei

There are two data sets that give information for nuclei with $6 < Z < 26$ with energy up to ~ 10 GeV/nucleon (Müller *et al.*, 1991; Engelmann *et al.*, 1990). At higher energy we also use RICH (Buckley *et al.*, 1994) and JACEE (Asakimori *et al.*, 1998) for CNO, JACEE only for Mg-Si, and JACEE and Ichimura *et al.* (1993) for $Z > 17$.

It appears difficult to fit the data sets well because of inconsistencies from one set to another in overlapping energy ranges. For this reason, we find a set of shape parameters for the fit of Eq. 1 that make a reasonable compromise and use the same values for all three groups, allowing only the overall normalization of each group to vary. Among other things, this crude approximation ignores the fact that the ratio of secondary to primary nuclei decreases as energy increases. Because of the small contribution to the all nucleon flux, this ambiguity is relatively unimportant for calculation of atmospheric muons and neutrinos, even at high energy where the problem is most acute. It does introduce significant uncertainty in the extrapolation to the PeV range for comparison with the all-particle spectrum measured by air shower experiments. The spectral index α for heavy nuclei is conservatively chosen to be 2.70, however the fits are equally good for values as low as 2.64.

3 Conclusions and open questions

3.1 Spectrum of nucleons

As noted above, it is the spectrum of nucleons that is most relevant for calculation of atmospheric muons and neutrinos. In Fig. 4 we show the all nucleon spectrum corresponding to the fits of Table 1 to Eq. 1 and separately the neutron component. The p/n ratio is important for the π^+/π^- and hence for the $\nu/\bar{\nu}$ ratio. Because nuclei and free protons have a different relation between energy per nucleon and magnetic rigidity, it is necessary also to distinguish between bound and free protons. In calculations that use the superposition approximation (e.g. Agrawal *et al.* (1996)) this is done by assuming that the number of bound protons is equal to the number of neutrons. The points labeled "FLUX4" correspond to the primary spectrum used in Agrawal *et al.* (1996). This same spectrum has been used by Battistoni *et al.* (2000) and for certain comparisons of calculations Engel *et al.* (2001). In view of the new measurements of the primary spectra of protons and helium, we recommend instead the use of the fits of Eq. 1 and Table 1.

The shaded band around the all-nucleon spectrum in Fig. 4 shows our estimate of the uncertainty. The same information is displayed more quantitatively in the lower panel of the figure, which shows the half-width of the error band as a fraction. These are rough estimates only, anchored at the low-energy end by the difference between BESS and AMS for protons and helium and increasing to $\sim$ $\pm 15\%$ above 1000 GeV. Note that this estimate assumes the calorimeter data of Ryan *et al.* (1972) can be renormalized downward by 25%, and that the protons and helium fluxes can be represented by simple (constant exponent) power laws up to the highest energy of interest. Less stringent assumptions would result in larger uncertainties. A critical work on this problem is in preparation. The differences between the new fits to the all-nucleon spectrum and those of Agrawal *et al.* (1996) are of the same order as the estimated uncertainties.

To estimate the implications of the remaining uncertainties in the primary spectrum for interpretation of measurements of atmospheric neutrinos, it is important to know the range of primary energies mainly responsible for the various data sets. Measurements of atmospheric neutrinos may be divided into two major groups, events in which the neutrino interacts inside the detector and neutrino-induced upward muons, which enter the detector from outside. At Super-Kamiokande (Fukuda *et al.*, 1998) events with contained vertices are further subdivided into sub-GeV and multi-GeV, while entering muons are classified as stopping or throughgoing. The shaded bars in Fig. 4 show ranges of primary energy per nucleon for these four classes of events. To illustrate, we can estimate the effect of changing from the spectrum of Agrawal *et al.* (1996) to the new all-nucleon spectrum. Keeping all other factors constant, use of the new fits would increase the predicted rate for sub-GeV events by about 10% and decrease the predictions for upward going throughgoing muons by about the same amount. More complete estimates would involve a convolution of the energy-dependent uncertainty in the primary spectrum with the response functions for the various neutrino measurements, as illustrated in Gaisser (2001).

3.2 Modulation and interstellar spectra

In view of the high quality of the recent measurements, it is appropriate to use them as the basis for a new interstellar spectrum as well. Assuming that solar modulation is relatively unimportant above 20 GV, we used the data above this rigidity to normalize the interstellar spectra. Assuming a power-law rigidity spectrum in interstellar space,

$$\frac{dN}{dR} = K \times R^{-\alpha}, \tag{3}$$

the spectral indices α are 2.74 (2.66) with normalization factors K of 15250 (7500) for H (He) nuclei.

We then used the force-field approximation (Fisk *et al.*, 1973) to attempt to fit the spectra of hydrogen and helium as measured by Sanuki *et al.* (2000) and Alcaraz *et al.* (2000a) at low energy. Accounting for solar modulation is important for accurate comparison between calculated and measured fluxes of atmospheric neutrinos in the sub-GeV energy range, especially at Soudan (Mann *et al.*, 2000) with its low local geomagnetic cutoff. At the time of the AMS and BESS98 flights (2-12 June and 29 July 1998, respectively) the level of solar activity was slightly elevated relative to solar minimum (of order 20% as measured by the level of cosmic-ray induced activity in neutron monitors). The modulation parameters needed are reasonable for this epoch of the solar cycle ($\Phi \sim 400$ to 500 MV), but the shape of the detected spectrum is not well reproduced. Forthcoming measurement from BESS near the present solar maximum will be helpful to obtain an improved treatment of solar modulation. Perhaps the question of the form of the interstellar rigidity spectrum can be finessed by using a rigidity version of the fits of Eq. 1 and a force-field approximation on this form to interpolate between solar maximum and solar minimum. Such an interpolating formula was used by Honda *et al.* (1995).

3.3 All particle spectrum

Heavy nuclei play a much more important role in the all-particle spectrum than for the calculation of uncorrelated muons and neutriinos. In order to fit the spectra of the nuclear groups from below 10 GeV to above a TeV, we made the simplifying assumption of a single, common power for all nuclei. While this is reasonable and adequate for calculation of neutrinos and muons, it can not replace a careful analysis and extrapolation of the measurements of nuclei in the energy range with $E_{total} > 1$ TeV. Nevertheless, it is useful to check that the representation we have chosen for heavy nuclei gives an extrapolation that is not inconsistent with air shower measurements of the all-particle spectrum. The current fits predict an all particle spectrum that at 100 TeV is consistent with the lower air shower estimates of Glasmacher *et al.* (1999). A decrease of the α values for heavy nuclei to about 2.66 would make the fits agree with the average cosmic ray flux estimated from air shower data.

3.4 Standard spectrum

We suggest that the spectrum derived from the new measurements and presented in Eq. 1 and Table 1 be used as a ‘standard spectrum’ for comparisons of calculations of uncorrelated atmospheric leptons.

References

Vivek Agrawal, T.K. Gaisser, Paolo Lipari & Todor Stanev, Phys. Rev. D53 (1996) 1314.

J. Alcaraz *et al.*, Physics Letters B 490 (2000) 27.

J. Alcaraz *et al.*, Physics Letters B494 (2000) 193.

K. Asakimori *et al.*, Ap. J. 502 (1998) 278.

G. Battistoni *et al.* Astroparticle Physics 12 (2000) 315.

R. Bellotti *et al.*, Phys. Rev. D60 (1999) 052002.

M. Boezio *et al.* Ap.J. 518 (1999) 457.

J. Buckley *et al.*, Ap J 429 (1994) 736.

Ralph Engel, T.K. Gaisser & Todor Stanev, this conference.

J.J. Engelmann *et al.*, Astron. Astrophys. 233 (1990) 233.

L.A. Fisk, M.A. Forman & W.I. Axford, J. Geo. Res. 78 (1973) 995.

Y. Fukuda *et al.*, Phys. Rev. Letters 81 (1998) 1562.

T.K. Gaisser, astro-ph/0104327 (to appear in Astropart. Physics).

M.A.K. Glasmacher *et al.*, Astroparticle Physics 10 (1999) 291.

M. Honda *et al.*, Phys. Rev. D52 (1995) 4985.

M. Ichimura *et al.*, Phys. Rev. D48 (1993) 1949.

Y. Kawamura *et al.*, Phys. Rev. D40 (1989) 729.

W. Anthony Mann (for the Soudan Collaboration), Nucl. Phys. Proc. Suppl. 91 (2000) 134.

W. Menn, *et al.*, Ap.J. 533 (2000) 281.

D. Müller *et al.*, Ap J 374 (1991)] 356.

M.J. Ryan, J.F. Ormes & V.K. Balasubrahmanyan, Phys. Rev. Letters 28 (1972) 985 & E1497.

T. Sanuki *et al.*, astro/ph-0002481

E.S. Seo *et al.*, Ap.J. 378 (1991) 763.