Discordant measurements of proton and helium fluxes below the knee energy region

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Abstract: The values of the spectral indices of the cosmic ions below the knee energy band are of notable importance for a quantitative account of the characteristic of the knee and the ankle of the differential energy spectrum of the cosmic radiation. Present available measurements of proton and helium spectral indices below the knee energy interval from a variety of experiments are examined. According to some measurements the proton dominance in the \( \frac{p}{He} \) flux ratio below \( 10^{13} \) eV transforms into a helium dominance above \( 10^{14} \) eV implying a break of the \( p \) and \( He \) spectral indices. On the contrary these trends remain unproven or disproved in other experiments. The relevance of these measurements to the origin of the knee and ankle is briefly presented and highlighted.

Introduction

What are the spectral indices of helium and proton below and close to the knee energy region? Measurements addressing to this empirical question are of the utmost importance not only for their intrinsic value but because they have fundamental implications in cosmic ray physics above the knee energy as explained below.

Figure 1 shows the proton and helium fluxes measured by four different experiments [9, 8, 18, 15] taken as an example (Bess, Atic, Runjob and Jacee) out of many others available, below the energy \( 3 \times 10^{15} \) eV. A dominance of the proton flux over that of the helium is clearly displayed in three experiments, being not evident in Jacee data. Figure 2 shows some measurements [16, 13] of the proton and helium fluxes by two experiments (Kascade and Eas-top) at higher energy: in this energy band the helium flux dominates over that of the proton. According to these results the proton and He spectral indices should somehow change in the transition region \( 10^{14} - 10^{15} \) eV. But this change is not empirically evident as argued by others [19].

Recent studies [3, 4, 2] providing a solution of the long standing problem of the knee and the ankle, adopt constant spectral indices for each ion of the cosmic radiation in the full energy band i.e. \( 10^9 \) to \( 10^{20} \) eV leading to an excellent agreement between computed and measured spectrum of the cosmic radiation (see figures 11 and 12 in [4]).

The anchorage of this postulate of constant spectral indices to physical reality is suggested by the form of the complete spectrum (all-particle spectrum). Three major accidents disrupt the regularity of the complete spectrum from being a perfect straight line segment in logarithmic scales of energy and intensity: the solar modulation at very low energy, the knee, and the ankle at very high energy. If these distortions are removed, a simple characteristic feature emerges: a remarkable linearity of the intensity versus energy (see figure 5 of [3]). But why should exist in nature the linearity of the complete spectrum, which is the sum of partial spectra, without assuming the linearity in the indices of the individual ions? There exist theoretical attempts [20, 6] predicting constant indices at the sources. A detailed study of the spectral indices of heavier elements is described in a forthcoming paper [1].

The following analysis is an attempt to ascertain if the proton and helium spectral indices in the energy region \( 10^{14} - 10^{15} \) eV are constant or they have one or more abrupt changes (breaks).
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Hypothesis of constant spectral indices

Let us introduce three alternative hypotheses for the proton and helium spectral indices denoted Hypothesis A, B and C. In the Hypothesis A, illustrated in figure 3, the proton and helium indices in the energy band $10^{11}$-$10^{15}$ eV are assumed to be constant. From the Atic and Jacee data shown in figure 1 the proton and helium fluxes are almost equal in the energy region $1-4 \times 10^{13}$ eV amounting to about $6 \times 10^{16} \text{ ions eV}^{-1.3}(m^2 \text{ sr s})^{-1}$. From the Kascade data shown in figure 2, in the restricted energy band $1-3 \times 10^{15}$ eV, the average proton and He fluxes are, respectively, 2 and $5 \times 10^{16} \text{ ions eV}^{1.5}(m^2 \text{ sr s})^{-1}$. Forcing constant spectral indices through Atic and Kascade fluxes, the indices of 2.68 and 2.54 for proton and helium, respectively, are obtained. This Hypothesis A, in spite of its simplicity, can accommodate neither the Eas-top data of figure 2 nor the proton dominance of the Runjob experiment displayed in figure 1. Notice that the proton and helium spectra obtained by Kascade using the Sibyll algorithm (not reported in figure 2 to avoid confusion) lead to the same inconsistency because error bars remain fairly small and the He/p ratio of about 2.4 is comparable to that of 2.3 obtained with the QGSjet algorithms (shown in figure 2).

Hypothesis of a break in the proton spectral index

As a consequence of the analysis made of the previous section more articulated elaborations referred to as Hypothesis B are required. The Hypothesis B admits the existence of a steep fall (break) of the proton spectrum in the energy decade $10^{13}$-$10^{14}$ eV as illustrated qualitatively in figure 3. Within this hypothetical condition the helium intensity measured by Kascade is compatible with the helium spectra measured by direct experiments at lower energies. A companion hypothesis in this energy band, contemplating a break in the helium index while preserving a constant index for proton is not favored by the Jacee data, those of
the Runjob or by a coherent matching between the cosmic-ray intensities measured by direct and indirect experiments.

Note however that the proton break is not convincing in any single experiment nor using the data of two different experiments (for instance, Runjob and Jacee). The break is excluded by the Runjob data (shown in figure 1) in the crucial and relevant energy decade before and close to the knee i.e. $10^{14} - 10^{15}$ eV.

### Hypothesis of parallel spectral indices for proton and helium

The oxygen spectrum has been recently measured by the Tracer experiment [17] at the maximum energy of $5 \times 10^{14}$ eV amounting to about $9.5 \times 10^{15}$ ions eV$^{1.5} (m^2 s sr)^{-1}$ as shown in figure 4. By extrapolating this value above $10^{15}$ eV with an index of 2.6, a general inconsistency with most results of the indirect experiments manifests. The carbon spectrum parallels the oxygen spectrum below $5 \times 10^{14}$ eV as indicated in figure 4 with a C/O flux ratio close to 0.6. The persistence of this constant ratio at higher energies (assuming C:N:O flux ratios of 0.6, 1/3, 1) results in a CNO intensity around the knee energy region significantly below the intensity measured by the Kascade experiment [16] by a crude factor 2.5. The discrepancy enlarges using the Eas-top CNO data [12].

One should notice the following two remarkable facts of the Kascade iron data. Firstly, the iron abundance in the energy band $1 - 4 \times 10^{15}$ eV measured by Kascade (Sybill) is 7.5 per cent, similar to that observed at lower energies (for instance, 9.94 per cent at 1 TeV, [7]). Secondly, the iron index measured by Kascade in a very large energy domain i.e. $10^{15.8} - 10^{16}$ eV is compatible with a constant value of 2.60, quite similar to that observed below $10^{14}$ eV (for instance, 2.60 at 1 TeV as compiled in [7]).

The N$_e$, Mg and Si data reported in figure 4 and others available indicate that neither the abundance nor the global index of the N$_e$-S group change in the energy range $10^{14} - 10^{15}$ eV with respect to the values (9.6 per cent and 2.64) at 1 TeV as compiled in [7]. The sum of the Fe intensity measured by Kascade in the energy band $1 - 4 \times 10^{15}$ eV with the extrapolated CNO and Ne-S intensities is in the same band $2.0 \text{ions eV}^{1.5} (m^2 s sr)^{-1}$ which is a fraction $0.23 \pm 0.04$ of the all-particle flux of $8.4 \text{ions eV}^{1.5} (m^2 s sr)^{-1}$ as measured by Kascade at $1 - 4 \times 10^{15}$ eV. Note that this global figure basically persists including the high neon abundance observed by Tracer [17]. Repeating the sum with the extrapolated Fe intensity based on the data of figure 4, instead of using the Ne intensity measured by Kascade, the resulting fraction is $0.21 \pm 0.04$. But these low fractions of heavy elements implies that proton and helium fluxes still dominate the cosmic ray spectrum around $1 - 4 \times 10^{15}$ eV. This Hypothesis C, termed quasi parallel hypothesis is a variant of the Hypothesis A and it empirically calls for constant spectral indices, at least up to $4 \times 10^{15}$ eV.

![Scheme to analyze H and He indices](image-url)
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Conclusions

Hypothesis A has multiple inconsistencies, even relaxing the intensity matching in different experiments. Hypothesis B would match the proton and helium spectra of direct and indirect experiments implying the existence of a pre-knee in the proton spectrum but it is not favored, or simply ruled out, by the Runjob data shown in figure 1. The Hypothesis C would question the dominance of heavy elements around the knee energy region 1-4 x 10^{15} eV reported or claimed by many EAS experiments. The outcomes of long duration balloon-borne instruments (see for example [5]) are likely to extricate soon the present experimental situation.

References