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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 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 concisely 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 [1, 2, 3, 4] taken as an example (Bess, Atic, Runjob and Jacee) out of many others available, below the energy 3×10^{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 [5, 6] 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 [7]. Recent studies [8, 9, 10] 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 [9]).

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 [8]). But why should exist in nature the linearity of the $complete\ spectrum$, without assuming the linearities of the individual ion spectra ? There exist theoretical attempts predicting constant indices of 2.5 [11] and 2.7 [12] at the sources.

The following analysis is an attempt to ascertain if the proton and helium spectral indices in the energy region 10^{11}-10^{15} eV are constant or they have one or more abrupt changes (breaks). The measurements of the spectral indices of heavier elements are discussed in a forthcoming paper [13].

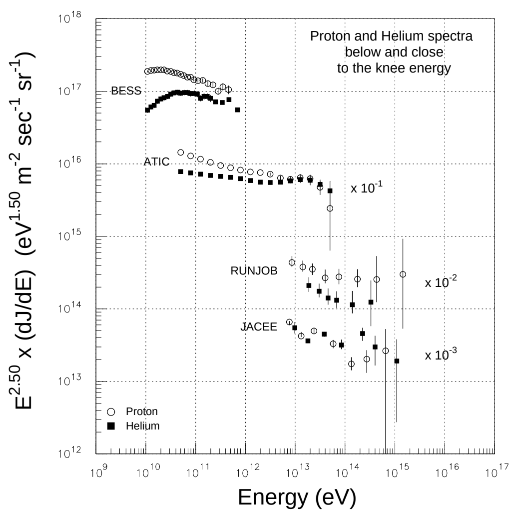

Figure 1: Dominance of the proton flux over that of helium below 3×10^{15} eV resulting from proton and helium spectra measured by some balloon-borne experiments (Bess, Atic, Runjob and Jacee) achieving individual identification of the cosmic ions (direct measurements).

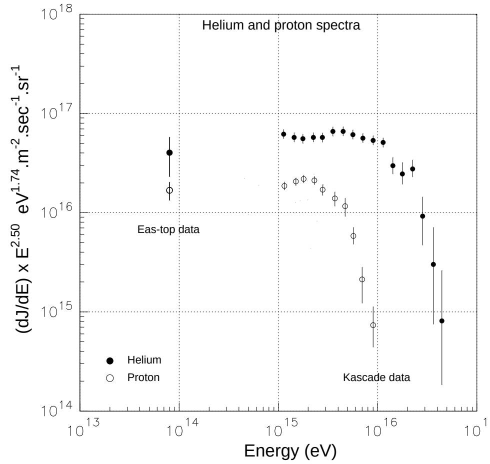

Figure 2: Dominance of the helium flux over that of proton measured by Eas-top and Kascade (QGSjet) experiments.

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 6×10^{16} $ions\, eV^{1.5}(m^2\ s\ sr)^{-1}$. 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 5×10^{16} $ions$ $eV^{1.5}(m^2\ s\ sr)^{-1}$. 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 accomodate 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 qualitatively illustrated 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 [14] at the maximum energy of 5×10^{14} eV amounting to about 9.5×10^{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 5×10^{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 [5] by a crude factor 2.5. The discrepancy enlarges using the Eas-top CNO data [15].

One should notice the following two remarkable facts of the Kascade iron data. Firstly, the iron abundance in the energy band 1-4×10^{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, [16]). 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 [16]).

The Ne, Mg and Si data reported in figure 4 and others available indicate that neither the abundance nor the global index of the Ne-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 [16]. The sum of the Fe intensity measured by Kascade in the energy band 1-4×10^{15} eV with the extrapolated CNO and Ne-S intensities is in the same band 2.0 $ions\ eV^{1.5}(m^2\ s\ sr)^{-1}$ which is a fraction 0.23 ± 0.04 of the all-particle flux of $8.4\ ions\ eV^{1.5}(m^2\ s\ sr)^{-1}$ as measured by Kascade at 1-4×10^{15} eV. Note that this global figure basically persists including the high neon abundance observed by Tracer [14]. Repeating the sum with the extrapolated Fe intensity based on the data of figure 4, instead of using the Fe intensity measured by Kascade, the resulting fraction is 0.21 ± 0.04. But these low fractions of heavy elements imply that proton and helium fluxes still dominate the cosmic ray spectrum around 1-4×10^{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 4×10^{15} eV.

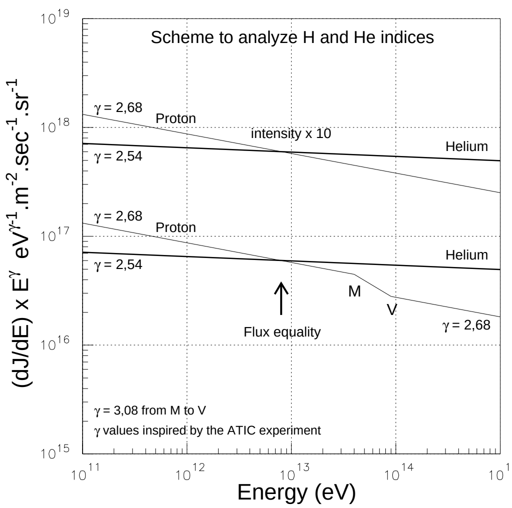

Figure 3: Hypothetical schemes of proton and helium spectral indices in the energy band 10^{12}-10^{15} eV. The $Hypothesis\ A$ adopts constant spectral indices giving a flux equality at the energy of 0.8×10^{13} eV. The $Hypothesis\ B$ conceives a possible (unproven) break of the proton index at the energy point denoted by M (4×10^{13} eV). Above the energy point V (9×10^{13}) the proton index is assumed to regain a constant value.

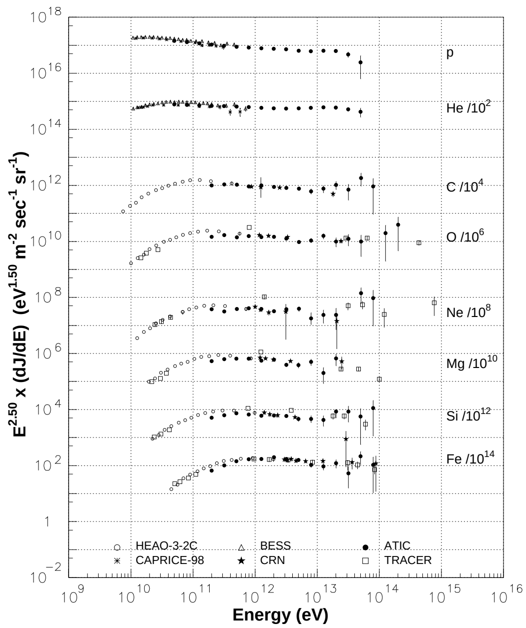

Figure 4: Intensities of individual ions measured by some experiments in the energy interval 10^{10}-10^{15} eV supporting the $Hypothesis\ C$.

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 1-4×10^{15} eV reported or claimed by many EAS experiments. The outcomes of long duration balloon-borne instruments (see for example [17]) are likely to extricate soon the present experimental situation.

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