About the energy interval above the ankle where the cosmic radiation consists only of ultraheavy nuclei from Zinc to the Actinides

Antonio Codino
University of Perugia and INFN, Via A. Pascoli, 06123 Perugia, Italy

Abstract

According to recent measurements the tendency of the chemical composition above the ankle is characterized by increasing fractions of intermediate and heavy nuclei and a dominance of light nuclei around the ankle. Calculation of the chemical composition in the range $3.5 \times 10^{18} - 5 \times 10^{19}$ eV according to new principles explains both the rising tendency of the heavy component. The calculation is prolonged to the adjacent interval $5 \times 10^{19} - 2.4 \times 10^{21}$ eV using the same theoretical background and some features of the observed cosmic-ray spectrum. It results that above the energy of $6.7 \times 10^{20}$ eV, where the flux is estimated to be $1.8 \times 10^{-30}$ particles/m$^2$ s sr GeV, the cosmic radiation consists only of nuclei heavier than Zinc. Measurements of the spectrum of present and past experiments are compared with the calculations.

Keywords:

1. Introduction

In the years 2005-2007 the HiRes Collaboration reported unequivocal evidence for a break of the cosmic-ray spectrum close and above to $5 \times 10^{19}$ eV [1]. This depression was confirmed by the Auger Collaboration at a significant lower energy [2] in the range $(2-3) \times 10^{19}$ eV. Presently this fundamental feature of the spectrum can be further investigated by the Telescope Array (hereafter TA) and Auger Collaborations which operate the two largest instruments gathering data above $10^{19}$ eV. The TA experiment located in Utah, North America, has a collecting area of about 700 Km$^2$ and is deployed in the historical site of the Fly’s Eye experiment which first recorded the fluorescence light of air showers in order to measure the energy of primary cosmic nuclei. The technique improves the energy resolution achievable otherwise. The Auger experiment located in Argentina, South America, has a collecting area of about 3000 Km$^2$. The difference in the collecting areas of the two instruments is reflected in the error bars of the measurements. In fact both instruments use the same hybrid technique which jointly exploits the fluorescence light yield and the muon density at ground of giant air cascades. This study necessitates the outcomes of both TA and Auger experiments in spite of the different precisions in the energy spectrum and chemical composition of two observatories.

The calculation of the cosmic-ray spectrum in the range $10^{19} - 2.4 \times 10^{21}$ eV presented in this paper is based on two empirical and one theoretical inputs designated by A, B and C. The limited size of this paper impedes a critical examination of the empirical inputs A and B. Consequently they are concisely summarized by two statements: (A) the chemical composition of the cosmic radiation evolves from light to heavy in the range $5 \times 10^{18} - 10^{20}$ eV [3, 4, 5, 6]; (B) there is a suppression in the energy spectrum above $2.6 \times 10^{19}$ eV [1, 2] with respect to a power-law extrapolation from the vast, adjacent, lower energy band, for instance the energy decade $2.6 \times 10^{18} - 2.6 \times 10^{19}$ eV [7]. Let us anticipate that the energy scales of the instruments are of critical importance for the validation of the energy spectrum computed in this paper above $2.6 \times 10^{19}$ eV because imperfections in the calibration of the energy scales affect also the observed fluxes. The Auger apparatus in the hybrid mode of operation at $10^{19}$ eV has an energy resolution of about 15 per cent and 10 per cent at $10^{20}$ eV. The TA instrument has a comparable energy resolution. As a matter of fact, if the energies reported in the published measurements are regarded as real and not preliminary, there was (2007) and there is (2015) an evident mismatch in the energy scales of the HiRes, Auger and TA instruments. Our sentiment is that the interexperiment calibration is not resolvable by a rigid shift in the range
Flux (m$^{-2}$sr s GeV)$^{-1}$

The power law of the energy spectrum of the cosmic radiation between $10^8$ and $2\times10^{20}$ eV measured by many experiments in more than 60 years. Up to the energy $2.6\times10^{19}$ eV the spectrum lies between two rails featured by an index of 2.67 and separated by a factor 38. The four major marks of the spectrum are indicated: the arc of the solar modulation below $10^{10}$ eV, the knee above $3.0\times10^{15}$ eV, the ankle at $3.5\times10^{18}$ eV and the break at $2.6\times10^{19}$ eV indicated by a vertical green segment. References to the data of the figure are elsewhere [10].

$10^{19}-10^{20}$ eV but involves non linear adjustments of the energy scales.

2. The power law of the energy spectrum of the cosmic radiation with a single index

A brief description of the third input C follows. Two decades of research via numerical simulation of the properties of Galactic cosmic rays have led to the explanation of the knee and ankle of the energy spectrum of the cosmic radiation [8]. The knee and the ankle are effects caused by the particle transport in the Galaxy (propagation effects) and not by the acceleration mechanism. This explanation is achievable only by introducing a notable assumption called Principle of Constant Indices [9]: the physical process accelerating cosmic rays in the Galaxy releases particles with an energy spectrum featured by a power law and an index of 2.67 ± 0.05 in the energy range $10^9-5\times10^{19}$ eV. Cosmic-ray propagation in the Galaxy has a negligible effect (see Chapter 17 of ref. 10) on the index inherent the acceleration process. Why this assumption is called principle is justified elsewhere [9]. The cosmic-ray spectrum shown in figure 1 in the limited range $10^9-2.6\times10^{19}$ eV is comprised between two rails, the blue lines, which differ by a factor 38 marked in fig. 1. The theoretical framework which explains the knee and ankle features also provides the characteristic gap expressed by the factor 38 [8].

Measurements of the energy spectra of 12 individual cosmic nuclei in the preknee region $10^{11}-10^{15}$ eV indicate that the spectral indices are compatible with a common value of $2.67 \pm 0.05$ [11]. Above the ankle energy the all-particle spectrum measured by Haverah Park, Yakutsk, Fly’s Eye, HiRes, AGASA, Auger and TA experiments is also compatible with the common index of $2.67 \pm 0.05$ observed in the preknee energy region (see for example fig. 2 of ref. 10).

Presently (2015) the physical process in the Galaxy accelerating cosmic rays in the range $10^9-2.6\times10^{19}$ eV is unknown, nevertheless it has some identified features [9, 10]: (1) it is distributed in space; (2) the accelerated particles obey a power law compatible with a single index of $2.67 \pm 0.05$ [11]; (3) it operates in the range $10^9-2.0 \times10^{20}$ eV. For conciseness in this paper the ensemble of these features is designated by Galactic Accelerator. Thus the Principle of Constant Indices [9] has been rephrased here by the properties of the Galactic Accelerator.

Other parameters of the Galactic Accelerator, conceivable a priori, could be the maximum energy of operation $E_{\text{max}}$ and the efficiency of the acceleration cycle versus energy denoted here $F$. The efficiency may be a function of some variables such as the energy, the time interval elapsed between the birth and the extinction of the cosmic ray, the nuclei abundances at the injection stage of the acceleration cycle and others. The acceleration cycle denotes a sequence of subprocesses that convert nuclei of the quiescent matter at the injection stage, up to the highest observed energies of $3 \times10^{20}$ eV [12] and eventually beyond this empirical limit. The Galactic Accelerator is expected to attain $E_{\text{max}}$ above $2.6\times10^{19}$ eV since below this energy the spectrum conforms perfectly to a power law with a parameter of 2.67 (see fig. 36 ref. 10). The tentative energy for $E_{\text{max}}$ resulting from this paper is likely to be $2.4 \times10^{21}$ eV regarded as a lower limit to the Galactic Accelerator.
Figure 2: Logical scheme with four bifurcation levels based on experimental data (energy spectrum and chemical composition) leading to the conclusion that quiescent nuclei are suppressed at the injection of the Galactic Accelerator (see also Fig. 3) above the energy thresholds $E_{LI}(Z)$ proportional to the atomic number of the nucleus.

3. The failure of particle injection to the Galactic Accelerator

Data useful for the following inference are the flux and the chemical composition in the range $10^{19.3} \times 10^{20}$ eV. A scheme of the logical paths of the inference is summarized in Fig. 2. Simplicity is an ingredient of the reasoning and intervenes in more than one link of the logical chain. The intrinsic acceleration process is also assumed not to alter the chemical composition at the injection, which is a common assumption recurrent in the literature.

A priori any incipient deviation from a power-law spectrum with a single parameter could be a depression or an enhancement. The data clearly manifest a depression above the energy $2.6 \times 10^{19}$ eV marked by a vertical green segment in Fig. 1. This particular energy is designated by $E_{LI}(H)$ and shortly by $E_{LI}$ where $H$ is for Hydrogen and $LI$ for Lack of particle Injection to the Galactic Accelerator. These wordings are justified below.

According to the Auger Collaboration the flux depression is halved with respect to a power-law extrapolation with a single parameter at the energy of $4.01 \pm 0.21 \times 10^{19}$ eV [13] which is quite consistent with $E_{LI} = 2.6 \times 10^{19}$ eV being this value the lowest energy where the deviation manifests itself (see Fig. 3 ref. 10). Since the hypothetical extragalactic component would yield an enhancement relative to the extrapolation, the observed spectrum rules out the extragalactic component (level 1 of Fig. 2). It follows that the Galactic Accelerator is still operating at this energy but a subprocess of the entire acceleration cycle initiates to fail, or equivalently, that the Galactic Accelerator is loosing its global efficiency exhibited and demonstrated below $2.6 \times 10^{19}$ eV via the constant index of $2.67 \pm 0.05$. Since the break in the spectrum at the energy $E_{LI}$ does exist [1, 2], either the intrinsic acceleration process is becoming inefficient or nuclear abundances are changing with the energy. The constraint of the simplicity dictates that the chemical composition and the acceleration efficiency do not vary simultaneously in the same energy range.

Notice the following important circumstance about the chemical composition of the cosmic radiation around and above to $10^{19}$ eV. The fractions of cosmic nuclei above $10^{19}$ eV cannot change by nuclear interactions as they do at lower energies. In fact the matter density in the interstellar medium is about $1 \ g/cm^3$. A nucleus crossing the Milky Way Galaxy at very high energy accumulates an average grammage between 6 to 8 millig/cm². Since interaction cross sections are known, it follows that the nuclear abundances cannot change by significant amounts. Due to this circumstance the fractions of nuclei at $10^{19}$ eV cannot be very different from those measured in the preknee energy region. Detailed calculations of the chemical composition in the range $10^{12}-10^{19}$ eV confirm this crude estimate (see Fig. 7 of The new horizon disclosed by the measurements of the chemical composition of the cosmic radiation above...
the ankle energy, Proceedings of Science, ICRC 2015, by A. Codino).

The measurements of the Auger and TA experiments indicate that the nuclei fractions change with the energy in the range $10^{19}$-$10^{20}$ eV (level 3 in fig. 2). Moreover they change in a very selective manner: the fraction of heavy ions augment with energy, or equivalently, the fraction of light ions decrease with energy (level 4 in fig. 2). The trend of the chemical composition with energy is certain but the absolute fractions of individual nuclei composing the cosmic radiation are still not known. The simple conclusion to be drawn is that: (1) the acceleration mechanism performs with the same efficiency above $E_{LI} = 2.6 \times 10^{19}$ eV and (2) the relative abundances of cosmic nuclei at the sources, before acceleration, change with the energy.

Major alternatives excluded by data as structured by the scheme of fig. 2 in the energy interval $E_{LI}-E_{\text{max}}$ are: (first alternative) (1) the efficiency of the acceleration process changes with the energy and (2) the relative abundances of the cosmic nuclei are energy independent; (second alternative) (1) the efficiency of the acceleration process does not change with the energy and (2) the relative abundances of cosmic nuclei are energy independent.

According to the conclusion given in fig. 2 the cosmic-ray flux is expected to abruptly fall as the energy increases and then to stabilize in plateaux (staircase pattern) as shown in figure 3. The gap between adjacent plateaux are directly proportional to the abundances of the nuclear species in the interval, $1 \leq Z \leq 92$. Thus the observed flux above $E_{LI}$ can deviate from the lower rail in fig. 1 by discrete amounts; amounts related to the fractions of nuclei composing the cosmic radiation. After the flux fall of a given nucleus, the spectrum regains the same slope of 2.67. Virtually each nucleus gives an intensity step. As the energy increases the lighter nuclear species disappear and the total flux grows thinner and thinner (see fig. 3).

4. The predicted energy spectrum in the range $10^{19}$-$2.4 \times 10^{21}$

The determination of the energy spectrum above $E_{LI} \equiv E_{LI}(H) = 2.6 \times 10^{19}$ eV requires two additional parameters: (I) the abundances of quiescent nuclei around $10^{19}$ eV at the injection; (II) the rule by which quiescent nuclei are filtered at the injection. The fractions of nuclei of the cosmic radiation normalized to Iron adopted in this calculation are: H .40, He .22, CNO .17, Ne-S
The relative amounts of nuclei at the injection do not suffice to calculate the energy spectrum because the particular energy of a nucleus $Z$ for which the injection process is hampered, is not assigned. The suppression mechanism delineated in fig. 3 only implies the disappearance of lighter nuclei before the heavier ones, as the energy increases. The simplest rule reflecting the fact that the chemical composition is becoming heavier above $10^{19}$ eV is to admit that nuclei of atomic number $Z$ are depleted above the threshold energies $E_{LI}(Z)$, that is, $E_{LI}(Z) = Z E_{LI}(H)$. The implication is that above the energy $E_{LI}(Z)$ the element $Z$ is not available as cosmic-ray source matter for any reason whatsoever. According to this linear relationship between $E$ and $Z$, Helium is expected to be depleted above the energy, $Z E_{LI}(H) = 5.2 \times 10^{19}$ eV, Nitrogen above $1.75 \times 10^{20}$ eV, Silicon above $3.5 \times 10^{20}$ eV, Fe nuclei above $6.7 \times 10^{20}$ eV and so on. If the rule were a linear relationship between $E$ and $A$, e.g. $E_{LI}(Z) = A E_{LI}(H)$ the incipient energies for the flux fall would change accordingly ($A$ is the atomic weight of the nucleus).

The predicted spectrum in the range $10^{19}-2.3 \times 10^{20}$ eV is given in fig. 4 (green squares) along with the positions of the threshold energies $E_{LI}(Z)$ of the abundant elements (H, He, C, N and O). The observed spectrum $E_{LI}$ is multiplied by $E^{2.67}$ and the blue line represents the flux extrapolation. The blue line is normalized to the Auger data at the intensity of $798 \text{ part/m}^2 \text{ sr GeV}^{1.67}$ [7] which corresponds to $1.159 \times 10^{-25} \text{ part/m}^2 \text{ sr GeV}$ in the flux unit reported in figure 1. Note that the normalization to the Auger data, and not to those of the TA experiment, is arbitrary.

Of course the flux in fig. 4 continues to decrease with the power law, which is the characteristic of the Galactic Accelerator, but there is an additional decrement caused by particle injection failure generating a first break above $2.6 \times 10^{19}$ eV (proton depletion). In fig. 5 the computed spectrum is extended up to $2.4 \times 10^{21}$ eV where Uranium injection failure is predicted to occur. Above the Fe threshold, $E_{LI}(26) = 26 E_{LI}(H) = 6.7 \times 10^{20}$ eV Iron disappears, giving rise to an almost vertical flux fall, due to the paucity of trans-iron nuclei. The trans-iron break is not out of reach of the planned JIM-EUSO experiment [17].
5. Comparison between computed and observed spectra

The spectra measured by TA and Auger Collaborations are compared with the predicted spectrum (green squares) in fig. 6. In order to better focus on the minute aspects of the spectrum a linear scale of energy is used. Below $8 \times 10^{19}$ eV the computed spectrum lies between the TA and Auger data and above this energy is compatible with the TA data while those by Auger are deficient. Notice that the average gap between TA and Auger fluxes above $8 \times 10^{19}$ eV attains almost an order of magnitude signalling problems in the measurement procedures.

Figures 7 and 8 show the comparison with the spectra measured by previous experiments having the largest exposures. An example of the spectrum measured by the Fly’ s Eye Collaboration, reported in the year 2000 [20], is shown in fig. 7 (black dots). In the half energy decade, between $5 \times 10^{19}$ eV and $10^{20}$ eV there is a hint for the proton depletion. Above $10^{20}$ eV some events are observed and the related flux is slightly above the prediction (green squares). The spectrum measured by the AGASA Collaboration [21] is shown in figure 8. With some imagination a small valley is visible in the interval $5 \times 10^{19}-10^{20}$ eV, compared to the extrapolated AGASA spectrum rooted in the range $(1-5) \times 10^{19}$ eV and represented by the black horizontal segment. Data points above $10^{20}$ eV in fig. 8 exceed the computed spectrum.

The four quoted experiments together do not disprove the calculations described in this paper. If the comparison is limited to the data collected by the hybrid techniques of the TA and Auger instruments, the predicted flux is too high versus Auger data but not versus TA data. Should the comparison include the fluxes reported by AGASA and Fly’ s Eye experiments, the data are evenly scattered around the predicted spectrum and no firm conclusion emerges, neither for rejection nor for validation. The rejection of the predicted spectrum only on the basis of the Auger flux above $8 \times 10^{19}$ eV (fig. 6) is premature until the large gap between TA and Auger spectra will not be clarified.

A second fact in favour of the computed spectrum reported in fig. 4 is that the Auger spectrum above $5 \times 10^{19}$ eV deviates from the extrapolation (blue line fig. 4) not by a power law with a single parameter but by steps, as the Auger data in fig. 9 demonstrate.

An alternative explanation of the observed cosmic-ray spectrum above $10^{19}$ eV recurrent in the literature is that an hypothetical extragalactic component of the cosmic radiation would suffer a depletion by the impact
with the ubiquitous photons of $6.7 \times 10^{-4}$ eV and density of 411 particles/cm$^3$. The depletion would commence above $6.0 \times 10^{19}$ eV according to the original calculations made sixty years ago and is usually described by a power law with a single parameter, much softer than 2.67. This hypothetical phenomenon is known as GZK effect. Let us mention that HiRes, Auger and TA Collaborations have explicitly claimed evidence for the GZK effect [1, 2]. The heavy chemical composition of the cosmic rays above $10^{19}$ eV makes this alternative explanation quite unlikely as explained elsewhere (The absence of the GZK depression in the energy spectrum of the cosmic radiation, ICRC 2013 by A. Codino).

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