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The new horizon disclosed by the measurements of the chemical composition of the cosmic radiation above the ankle energy

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The measurements of the chemical composition of the cosmic radiation in the last years above the ankle energy have modified the foundation of Cosmic Ray Physics and they have simple and imperious interpretations: (1) high energy cosmic rays in the band 3.5×10^{18}-3.0×10^{20} eV do not have an extragalactic origin; (2) the cosmic nuclei above the ankle are not dominated by protons but they have a mixed composition with a rising fraction of heavy nuclei up to the highest observed energies $\sim 4 \times 10^{19}$ eV where Fe nuclei seem dominant; (3) the cutoff of the spectrum observed at the incipient energy of (2.5-3)$\times 10^{19}$ eV is not due to the collisions of the extragalactic cosmic protons with the ubiquitous cosmic photons of 6.76×10^{-4} eV but to a galactic process (absence of GZK effect). The consistency of the experimental data on the chemical composition of various experiments are presented and shortly discussed. The focus of the presentation is on the severe and illuminating constraints implied by these measurements on the quest for the mechanism accelerating cosmic rays in the Galaxy, which is presently unknown.

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1. Introduction

The identification of individual nuclear species of the cosmic radiation with electronic techniques is presently achievable up to energies of $5 \times 10^{14} eV$. At energies above $10^{18} eV$ detectors determine some pertinent parameters of giant atmospheric cascades by which, in principle, the segregation of all primary nuclei in a few groups might be achieved. The Volcano Ranch, Yakutsk, Haverah Park, HiRes, Akeno-Agasa apparata tried to separate all nuclear species in two groups: light and heavy nuclei with a dividing line rather vague. In spite of the effort the measurements on the chemical composition of these experiments were ambiguous, and in some cases, contradictory: for example, the reanalysis of Akeno-Agasa data [1] did not exclude a rather heavy composition the interval 5×10^{17}- $5 \times 10^{19} eV$ while the Yakutsk data [2] , in the same energy range, indicated a chemical composition becoming light and light with increasing energy. The long period of uncertainty of about half a century came to a conclusive clarification in the year 2007 when the Auger Collaboration reported redundant evidence that the fraction of heavy nuclei above the ankle energy ($3.5 \times 10^{18} eV$) is substantial. Even more important, it resulted that the chemical composition of the cosmic radiation evolves from light to heavy in the band 10^{18} - $4.12 \times 10^{19} eV$ regardless of the absolute value of the nuclei fractions. The redundant evidence is provided by the consistent results obtained by three independent method of measurements of the chemical composition feasible by the Auger Observatory. The measurements of the Auger Collaboration are of historical importance and their impact affects three major heterogeneous areas: (1) the observed heavy chemical composition indicates that cosmic rays are galactic, at least, up to 5×10^{19} eV ; no argument impedes to admit that cosmic rays above this energy, sources and acceleration mechanism, continue to be galactic in nature, up to the highest observed energies, 3×10^{20} eV ; (2) the widespread, long standing theoretical prejudice that ultrahigh cosmic rays are extragalactic was finally removed from the arena of Cosmic Ray Physics ; (3) the measurements of HiRes Collaboration on the chemical composition, which favoured pure proton content of cosmic radiation above the ankle energy, finally clashed into an empirical barrier e.g. the measurements of another more powerful instrument using the same technique. Explicit skepticism on the HiRes outcomes on the chemical composition was vented in other works [3, 4].

2. The chemical composition above the ankle measured by three independent methods.

The measurements of the chemical composition of the cosmic radiation via the variable $\sigma(X_{max})$ reported by the Auger Collaboration [5, 6, 7] in the years 2007, 2011 and 2013 are shown in Fig. 1. The technique of the measurement reconstructs the longitudinal profile of the flourescence light generated in the cascade and determines the width of the profile with the appropriate interpolation function. Qualitatively, at a given energy, pure proton cascades have widths larger than pure iron cascades. The computed widths for protons (see Fig. 1) are about 65.0 g/cm^2 at 10^{18} eV and 58.0 g/cm^2 at 4.0×10^{19} eV while for Iron, at the same energies, are 23.9 g/cm^2 and 22.1 g/cm^2, respectively . Thus, the computed difference in the widths of the flourescence profile of these two extreme nuclei is about 40.5 g/cm^2 at 10^{18} eV and 36.1 g/cm^2 at 4.0×10^{19} eV . The numerical figures quoted above, shown in Fig. 1, are computed by the Auger Collaboration with the code

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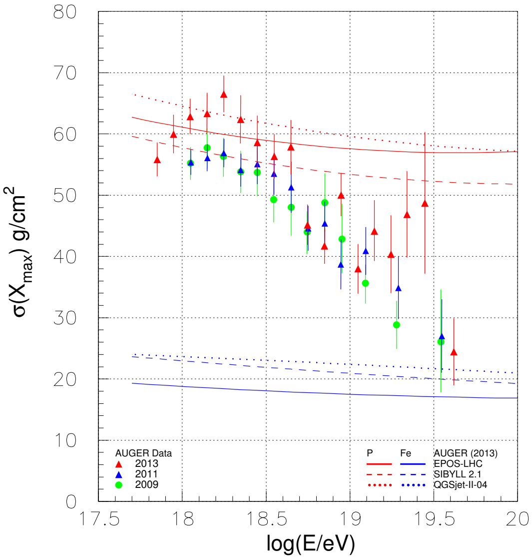

Figure 1: Width of the longitudinal profile of the fluorescence light $\sigma(X_{max})$ measured by the Auger Collaboration versus energy. During the years, around the ankle, data points migrate to a high proton fraction, which is incorrect according to the TCI.

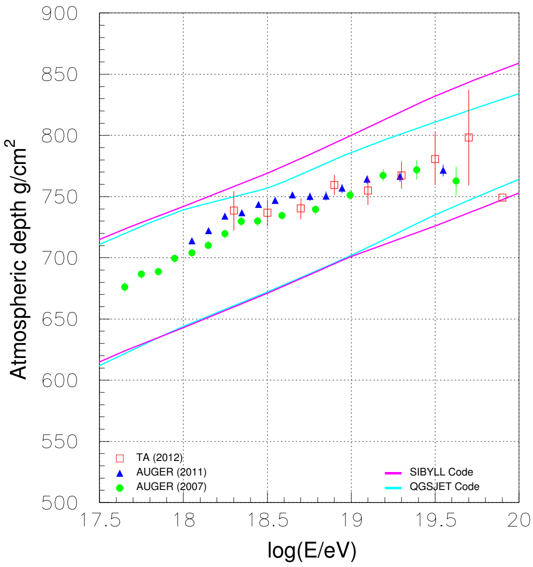

Figure 2: Mean impact point X_{max} of primary nuclei in the Earth atmosphere measured by Auger and TA experiments as a funcion of energy up to $10^{20} eV$.

QGSjet-II-04. The data in Fig. 1 show a general tendency : the width of the longitudinal cascade profile versus energy decreases going from about 60-65 g/cm^2 down to 24-26 g/cm^2 at 4.0×10^{19} eV . This behaviour is indicative of a chemical composition evolving from light to heavy in the energy band, 10^{18} - 4.0×10^{19} eV .

Notice that the most recent measurements shown (red triangles, Fig. 1) exhibit the same trend of the early data (green dots, Fig. 1) but the tendency for heavy composition is further corroborated in spite of the visual aspect of the data; in fact the maximum gap between the mean largest width of 65 g/cm^2 occurring around 10^{18} eV and the mean narrowest width of 22.2 g/cm^2 at 4.0×10^{19} eV, e.g. 43.0 g/cm^2, is slightly increased with respect to the corresponding numerical figures of the previous data sample (2007) e.g. 39.9 g/cm^2 . The systematic uncertainty in the measurements is estimated to be 5.0 g/cm^2.

A second method of measuring the chemical composition is to determine the impact point of primary cosmic rays via the atmospheric depth denoted X_{max} from an ideal surface concentric to the Earth placed at zero g/cm^2. Due to nuclear interaction cross sections, protons penetrate in the Earth atmosphere deeper than Iron nuclei. The X_{max} of cosmic nuclei versus energy measured by the TA and Auger experiments [8, 9] in the interval 3×10^{17} - 10^{20} eV is reported in figure 2 along with theoretical evaluations of X_{max} (turquoise and pink profiles).

The third method of measuring the chemical composition takes advantage of timing characteristics of the fast particles of the cascade front hitting the ground. Inclined showers relative of

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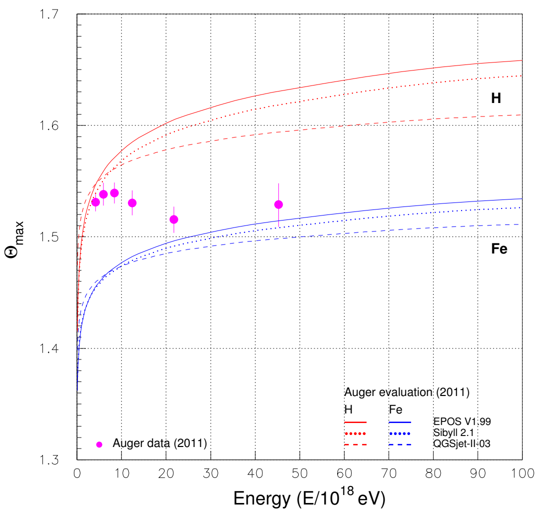

Figure 3: Measurements of the chemical composition exploiting the timing characteristics of the cascade front hitting the ground along with the theoretical evaluation of θ_{max} according to Auger Collaboration [10].

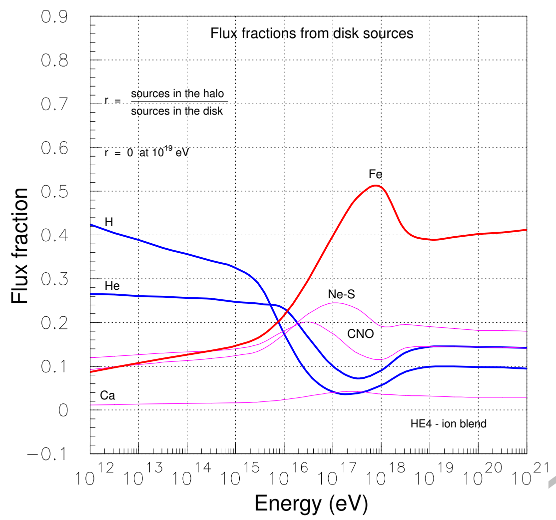

Figure 4: Nuclei abundances versus energy in the range 10^{12}-5×10^{19} eV computed with the *Theory of Constant Indices* (TCI). Above the nominal energy of 5×10^{19} eV the TCI is not applicable.

the zenith angle lend themselves to separate light and heavy primaries [10] from the timing imbalance of two appropriate symmetric points of the shower front. The feasibility of the technique was tested during many years with the Haverah Park detector and revived and operated in the colossal instrument deployed in Argentina. Fig. 3 reports the chemical composition measured by this technique along with the estimates of the instrument response made by the Auger Collaboration for pure proton cascades (upper red curves) and pure Fe cascades (lower blu curves). The outcome of Fig. 3 corroborates the tendency of the chemical composition shown in Fig. 1 and Fig. 2.

The data survey in the interval 10^{18} - 4.12×10^{19} eV indicates that cosmic rays have an ascending, relevant fraction of heavy nuclei.

3. The observed chemical composition and the absence of the hypothetical GZK effect.

The intermediate and heavy nuclei content of the primary cosmic radiation above the ankle imply that cosmic-ray sources and the related acceleration mechanism are located in the Milky Way Galaxy. The continuity of the spectrum descending from the *Principle of Constant Indices* above 5×10^{19} eV corroborates this conclusion which is of invaluable importance in the quest for the Galactic accelerator. This opens exciting perspectives for future achievements.

Photons with a black-body spectrum and peak energy of 6.76×10^{-4} eV populate the cosmic space everywhere with a density ρ_γ of 411 photons/cm^3 . The impact of the hypothetical cosmo-

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logical protons on the ubiquitous fossile photons via photonuclear reactions , $p\ \gamma \rightarrow \pi^+ + n$ and $p\ \gamma \rightarrow \pi^0 + p$, is expected to distort the cosmic-ray spectrum above 6×10^{19} eV with maximum deformation around 10^{20} eV (GZK effect). The cross sections σ for the aforementioned reactions above threshold are 120.0×10^{-27} cm^2, and therefore, the length of a photon column necessary to make a $p\ \gamma$ collision is $1/\sigma\ \rho_\gamma$. This length is about 6.5 *Megaparsec*. Contrary to the expected kinematical features of the hypothetical GZK effect, the flux fall in the cosmic-ray spectrum measured by Auger experiment is not at 10^{20} eV but an order of magnitude below, at 2.6×10^{19} eV. This gap is more than sufficient to reject the incorrect interpretations of Auger Collaboration of the distortion of the energy spectrum via the GZK effect above 2.6×10^{19} eV. A similar incorrect interpretation has been also claimed by HiRes and TA Collaborations.

This particular topic is debated in another paper (The Absence of GZK Suppression in the Energy Spectrum of the Cosmic Radiation, by A. Codino, ICRC 2013, Rio de Janeiro, Brasil).

4. The chemical composition resulting from cosmic-ray sources placed in the disc.

The chemical composition expressed via the relative fractions of six nuclear species in the band 10^{12} - 5×10^{19} eV are calculated and shown in Fig. 4. Six nuclei are more than adequate in the comparison with the available data. The theoretical framework of the calculation referred to as *Theory of Constant Indices* (hereafter TCI) is given in another paper at this Conference (The Knee and Ankle Features derived from the Principle etc.). The nuclei fractions of fig. 4 derive from the energy spectra calculated by the TCI and they are standard results. In this calculation cosmic-ray sources are placed in the disc volume of 353.4 kpc^3 and they are uniformly distributed. The disc has a radius of 15 kpc and half thickness of 250 pc. Cosmic rays from disc sources are referred to as *disc component*. The conversion of the nuclei fractions of figure 4 into the mean mass <log(A)> is shown in Fig. 5 (blu upper curve). The classical variable <log(A)>, the mean logarithmic mass, where A is the atomic mass of the primary nucleus, is used in the studies of giant cascades in air and it is amply discussed in the literature.

The disc component (blu curve in Fig. 5) gives a fraction of heavy nuclei significantly greater than that observed by the Auger Collaboration in the vast energy interval, 3.5×10^{18} - 5×10^{19} eV . If the measurements reported fig. 1, 2 and 3 are substancially correct , the <log(A)> profile of the disc component predicted by the TCI in the range 10^{18} - 5×10^{19} eV (blue upper curve Fig. 5), being too high, disagrees with the data. Notice that it is in excellent accord in the range 10^{12}-10^{18} eV with many experimental data (see Section 5 of Ref. 11) .

Long and vain efforts were dedicated in the years 2007-2008 to find out a viable solution in the context of TCI to explain the rise of the chemical composition in the range 3×10^{18} - 5×10^{19} eV without introducing additional new parameters.

The conclusion is that the only way to obtain a chemical composition which rises with the energy in the band 3×10^{18} - 5×10^{19} eV using the TCI is to postulate a physical process that reinject cosmic rays from the halo to the disc. These reentrant particles are called *extradisc component*. The necessity of introducing the extradisc component became inescapable in 2007, when the first Auger data on the chemical composition became known [8].

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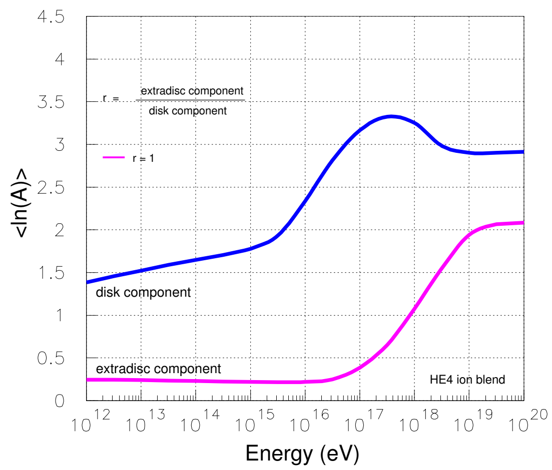

Figure 5: Profile of the chemical composition of the cosmic radiation of the disc (blue upper curve) and extradisc components. The relative amounts of the six nuclei at 10^{12} *eV* are called HE4 ion blend.

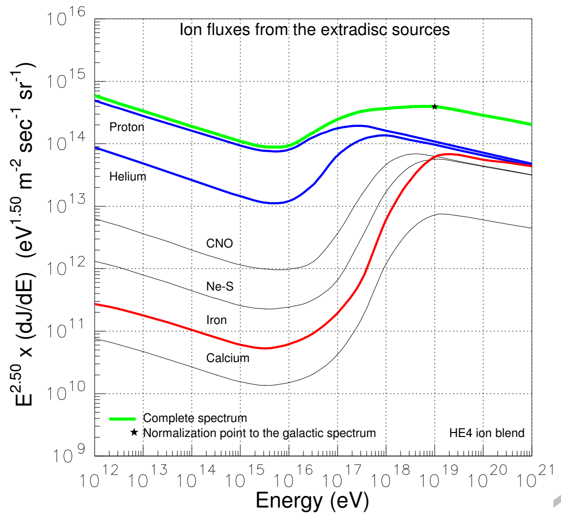

Figure 6: Energy spectra of the extradisc component observed at Earth normalized at the flux of 3.9×10^{14} $particles/m^2 s\ sr$ $eV^{1.5}$ at 10^{19} *eV* (black star). *Complete Spectrum* denotes the all-particle spectrum with electrons, positrons and antiprotons excluded.

5. Chemical composition above the ankle resulting from the disc and extradisc components.

The energy spectra of the extradisc component (reentrant particles from the halo) are shown in Fig. 6 and the corresponding <log(A)> in Fig. 5 (lower pink curve). It results that the chemical composition of the extradisc component in terms of <log(A)> is lighter than that of the disc (Fig. 5, lower pink profile) at the same energy : heavy nuclei are destroyed more efficiently than light nuclei while displacing in the disc, because interaction cross sections depend on the atomic weight A. This is the simple and sole mechanism at work being all the parameters of the calculations unchanged with respect to those utilized for the energy spectra of the disc component. The disc-to-extradisc flux ratio is denoted by r.

No new parameter is introduced in calculating the spectra of reentrant particles if r = 1 : particles evading into the halo reenter with no amplification or suppression caused by unknown or exotic processes. The extradisc flux is normalized at the value of 3.9×10^{14} $particles/m^2 s\ sr\ eV^{1.5}$ at 10^{19} *eV* (black star in Fig. 6) which is equal to that of the disc component, and accordingly, r = 1. An example of calculation of nuclei fractions with r = 2 is shown in Fig. 7. The sum of the disc and extradisc components yields the chemical composition in terms of $\langle$log(A)$\rangle$ reported in figure 8 where the parameter r is varied from 1 up to r = 10. Notice that the disc component is included in the results of Fig. 7 and 8.

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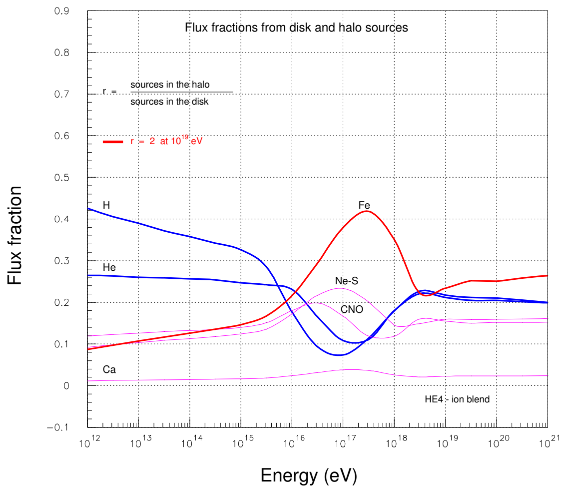

Figure 7: Nuclei abundances versus energy of the extradisc component with *r*=2 in the range 10^{12} - 5×10^{19} *eV* computed with the *Theory of Constant Indices* (*TCI*). The value *r*=2 is an illustrative example.

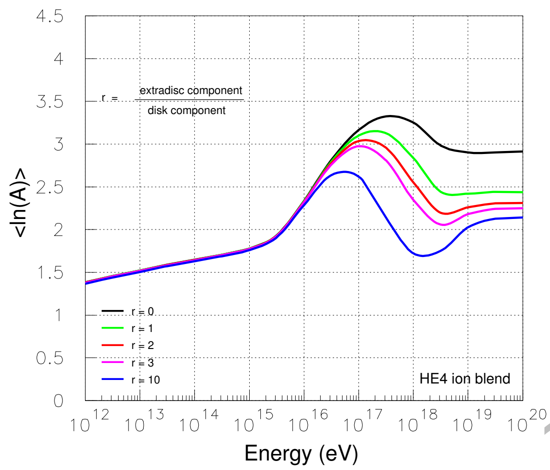

Figure 8: Chemical composition of the cosmic radiation versus energy of the disc and extradisc components according to the TCI. The mean logarithmic mass <log(A)> has a minimun around the ankle then it gently rises up to about 5×10^{19} *eV*. Above the nominal energy of 5×10^{19} *eV* the TCI is not applicable.

The <log(A)> profiles of the disc and extradisc components shown in Fig. 8 have two major interesting features: (1) they rise with the energy in the range (3-4) $\times 10^{18}$ - 5×10^{19} ; (2) they exhibit a minimum around the ankle energy. Both these fundamental features are in agreement with the Auger data (see Fig. 17, Section 5 in Ref. 11).

6. Discussion and conclusion

The concept of reinjection of cosmic rays from the halo is the only way out according to the TCI to explain the chemical composition in the range 10^{18} - 5×10^{19}. The necessity of admitting reentrant particles from the halo volume is not extraneous Cosmic Ray Physics at very low energies.

This necessity originates from the comparison of the residence time of cosmic rays in the Galaxy measured by radioactive clocks with that inferred by the secondary-to-primary flux ratio (B/C flux ratio, sub-Fe/Fe flux ratio, etc) . The residence times based on radioactive clocks give 15-20 millions years while that extracted by the secondary-to-primary flux ratio is about 5-7 millions years. The inconsistency have been noticed by a number of authors. In fact with an average gas density of 1 atom/cm^3 in the disc and a residence time of 15-20 millions years the resulting average grammage encountered by cosmic rays is about 20-25 g/cm^2. With these numerical figures the B/C flux ratio above 50 GeV/u would exceed the observed value of 0.09-0.1 reported by many

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experiments up to 7000 GeV/u (Tracer and Runjob experiments). The standard removal of this inconsistency admits that cosmic rays wander a larger fraction of their lifetime in the halo where the matter density decreases by a factor of about 10^2 relative to disc. The resulting average matter density encountered by cosmic rays is accordingly reconciled with secondary-to-primary flux ratios. The concept of reentrant particles at very low energy is either explicitly or silently admitted in the literature by most authors.

A quantitative account of the chemical composition in the range 3×10^{18} - 5×10^{19} eV according to TCI resonates to the same concept of reentrant particles at very low energy just mentioned. A new physical process is at work since above the ankle energy, 3×10^{18} - 5×10^{19} eV, cosmic rays displace in the quasi rectilinear propagation mode. In this propagation regime the bending power of the galactic magnetic field is highly inefficient to deflect particles and hence the standard magnetic diffusive transport is alien to the physical process causing particles to reenter. In fact detailed Monte Carlo studies [12] demonstrate that the disc albedo of reentrant particles from the halo is 5×10^{-4} even at very low energies.

If the results shown in Fig. 8 are correct along with those on the chemical composition of Fig. 7, it descends that cosmic rays evade from the source regions in the disc volume, occupy the halo and then, they reenter to the disc volume. As argued above the magnetic field is extraneous to this phenomenon. As a consequence there is a physical process operating in the Galaxy, still not identified, which forces cosmic rays to reenter. According to the TCI this is by far the most astonishing and important result produced by the Auger instrument since its first days of operation .

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