Implications of the UHECRs penetration depth measurements

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The simple interpretation of PAO’s UHECRs’ penetration depth measurements suggests a transition at the energy range $1.1 - 35 \cdot 10^{18}$ eV from protons to heavier nuclei. A detailed comparison of this data with air shower simulations reveals strong restrictions on the amount of light nuclei (protons and He) in the observed flux. We find a robust upper bound on the observed proton fraction of the UHECRs flux and we rule out a composition dominated by protons and He. Acceleration and propagation effects lead to an observed composition that is different from the one at the source.

Using a simple toy model that take into account these effects, we show that the observations requires an extreme metallicity at the sources with metals to protons mass ratio of 1:1, a ratio that is larger by a factor of a hundred than the solar abundance. This composition imposes an almost impossible constraint on all current astrophysical models for UHECRs accelerators. This may provide a first hint towards new physics that emerges at $\sim 100$ TeV and leads to a larger proton cross section at these energies.

Consider a cosmic ray flux composed of $N$ species each with a fraction $f_j$, a mean penetration depth, $\langle X_{\text{max}} \rangle_j$, and RMS variation $\sigma_j$. At each energy these are related to the measured mean and RMS values as:

$$\sum_{j=1}^{N} f_j \langle X_{\text{max}} \rangle_j = \langle X_{\text{max}} \rangle,$$

$$\sum_{j=1}^{N} f_j (\sigma_j^2 + \langle X_{\text{max}} \rangle_j^2) - \langle X_{\text{max}} \rangle^2 = \sigma(\langle X_{\text{max}} \rangle)^2. \quad (2)$$

In the following we examine several possible solutions of these equations for different compositions.

1 The interactions between UHECRs and atmospheric particles takes place at CM energies of $\sim 100$ TeV. This is about a hundred times higher than CM energies in which cross sections have been measured.

2 While PAO has the best statistics, the High resolution fly’s eye (HiRes) and the telescope array (TA) observatories\textsuperscript{3,4} composition results are consistent with proton dominated composition all the way up to the high end of the spectrum. This disagreement among the different observatories is still to be settled.

Consider, first, a mixture of protons (denoted p) and another arbitrary component, denoted 0. This arbitrary component may be a single species or a combination of a few. The condition $\sigma_0^2 > 0$ yields an upper bound on $f_p(E)$:

$$f_p \leq \frac{1 + \sigma(\langle X_{\text{max}} \rangle)^2 + \langle (X_{\text{max}}) - \langle X_{\text{max}} \rangle_p \rangle^2}{\sigma_p^2} - \left( \sqrt{1 + \frac{4 \sigma(\langle X_{\text{max}} \rangle)^2 + \langle (X_{\text{max}}) - \langle X_{\text{max}} \rangle_p \rangle^2}{\sigma_p^2}} - \frac{4 \sigma(\langle X_{\text{max}} \rangle)^2}{\sigma_p^2} \right). \quad (3)$$

Fig. 1 depicts the upper limit obtained using the observed values of $\langle X_{\text{max}} \rangle$ and $\sigma(\langle X_{\text{max}} \rangle)$ and the simulated values of $\langle X_{\text{max}} \rangle_p$ and $\sigma_p$. The maximal proton fraction is smaller than 50% at $E > 10^{19}$ eV and it decreases below 30% at higher energies. This upper bound depends only on the observed PAO data and on the shower simulation results for protons (it does not even depend on the shower simulations for nuclei). It is independent of the acceleration or propagation of the UHECRs. When we replace the hypothetical ingredient with any composition of He, N, Si and Fe the upper bound on $f_p$ at the two highest energy bins is smaller by $\approx 10\%$ than the upper limit derived using $\sigma_0 = 0$.

Protons and Fe survives best the interactions with the cosmic photon field while propagating from the sources to Earth\textsuperscript{5,6}. As such they are the most natural UHECR ingredients. However, with just two components the system of eqs. (1)-(2) is overdetermined. Wilk and Wlodarczyk\textsuperscript{7} have shown that there is no consistent solution for protons and Fe within the error bars of the PAO data and the shower simulations.

Eqs. (1)-(2) have a marginal ($\chi^2/dof \approx 1$) solution for a mixture of protons and He (see also\textsuperscript{8}). However, when propagation effects are taken into account this composition can be ruled out. He nuclei photodisintegrate rapidly on their way from the sources to Earth. For simplicity we neglect redshift effects and assuming a uniform distribution of sources. Under this approxi-
protons with energy $E$. Most of the He nuclei disintegrate producing secondary protons, the flux, $J_{\text{p,sec}}$, is $(1 - f_p(E)) J(E)$, where $f_p(E)$ is the fraction of He nuclei with energy $E$ surviving and reaching Earth. For a given observed He flux, $(1 - f_p(E)) J(E)$, the flux at the source is $F_{\text{GZK,He}}(E) = l_{\text{He}}/E$.

Since $F_{\text{GZK,He}}(E)$ is $\ll 1$ most of the He nuclei disintegrate producing secondary protons with energy $E/4$. The resulting secondary proton flux is:

$$J_{\text{p,sec}}(E) \approx 4(1 - F_{\text{GZK,He}}(4E))^3 \frac{(1 - f_p(4E)) J(4E)}{F_{\text{GZK,He}}(4E)}$$

Using the upper bound on $f_p(E)$ obtained earlier (eq. 3), we find (see fig. 2) that this secondary proton flux is larger than the maximal proton flux allowed.

Kampert and Unger [15] have shown that a mixture of protons, He and intermediate elements like N, Si and Fe can provide a solution of eqs. (1) and (2) for the observed composition which is within the uncertainties of the observed data and the simulations. However, as we have seen for p and He, to determine the sources’ composition we need to take propagation effects into account. Moreover, since different species are accelerated differently within a given accelerator, acceleration should also be considered. To examine these effects we consider a toy model based on only two components: protons and Fe. As mentioned earlier, this composition cannot satisfy equations (1) and (2) and other intermediate elements in addition to Fe are needed. Therefore, when we examine a proton and Fe composition we consider only the overall spectra and $(X_{\text{max}})$ and we ignore, for simplicity, the RMS data. This simple example is sufficient for demonstrating the nature of the problem.

Any electromagnetic acceleration process that accelerates protons to energy $E$ accelerates nuclei (with charge $Z$) to energy $E^{1/Z}$. This suggests a natural explanation for the transition in composition: the source accelerates protons to a power law energy distribution, $E^{-\alpha}$ up to some maximal energy where a gradual cutoff begins. The same source accelerates nuclei to the same power law but up to an energy that is $Z$ times larger. This naturally produces a heavier observed composition than the one at the source and may suggest that the drop at very high energies in the UHECR flux is not necessarily due to a GZK effect but simply due to lack of available accelerators that can accelerate UHECRs to extremely large energies [18]. We characterized the accelerator’s cutoff by an unknown function of the rigidity, $g(E/Z)$, with $0 \leq g(E) \leq 1$ and $g(E) = 1$ at low energies.

However, before adopting this model propagation effects should also be taken into account. Like acceleration, propagation in the IGM magnetic field depends on the rigidity. On the other hand GZK attenuation depends on the nucleus at hand. In this energy range (1.1-35 EeV), it is negligible for protons but it is significant for all nuclei. We characterize the propagation effects using $F_{\text{GZK,Fe}}/l_{\text{c}}$ [16]. Under these assumptions the total observed UHECRs flux is:

$$J(E) = c_p g(E) E^{-\alpha} + c_{\text{Fe}} F_{\text{GZK,Fe}}(E) g(E) \frac{E}{26} E^{-\alpha}$$

3 (i) The protons GZK distance is comparable to the horizon distance at these energies. (ii) We have overestimated here the GZK distances of $^4\text{He}$ and $^3\text{H}$ as equal to the GZK distance of $^4\text{He}$.
Where $c_p, c_{Fe}$ are normalization factors for the proton and Fe nuclei fluxes respectively. $c_p$ is obtained by the condition $g(E) = 1$ at the minimal energy. The normalization of $c_{Fe}$ is such that $c_{Fe}/c_p$ equals the Fe nuclei to protons number ratio at the source (before acceleration). Using the proton fraction $f_p(E) = c_p g(E) E^{-\alpha} / J(E)$ and $g(E/26) = 1$, which is valid over the relevant energy range (1.1-35 EeV) eq. (5) becomes:

$$J(E)(1 - f_p(E)) = \frac{c_{Fe}}{26^{1-\alpha}} E^{-\alpha}, \tag{6}$$

We solve eq. (4) for $f_p(E)$ using the measured $\langle X_{max}\rangle$ and the simulated values for protons and Fe. Now that all the quantities at the l.h.s of (6) are known we fit a power law ($\langle X_{max}\rangle$ and the simulated values for protons and Fe. Now that all the quantities at the l.h.s of (6) are known we fit a power law ($E^{-\alpha}$) to the l.h.s to to obtain $\alpha$ and $c_{Fe}$. The best fit results are: $\alpha = 2.1 \pm 0.1$, $c_{Fe}/c_p = (2.2 \pm 0.6) \cdot 10^{-2}$, with $\chi^2/dof = 0.21$.

The number ratio we obtained corresponds to a mass ratio of $\approx 1 : 1$. A similar analysis with Si instead of Fe yields $\alpha = 1.9 \pm 0.1$, $c_{Si}/c_p = (5 \pm 1) \cdot 10^{-2}$, with $\chi^2/dof = 0.4$. The mass ratio is again $\approx 1 : 1$. As both Fe and Si show almost the same trend a composite solution that will satisfy both the $\langle X_{max}\rangle$ and $\sigma(X_{max})$ data will have similar features and a $\sim 1 : 1$ mass ratio between the protons and the metals.

Note that we have neglected secondary protons arising from photodisintegration. Taking those into account would have resulted in even higher metallicity. Shifting the observed energies by about 20%, as suggested by comparison of the PAO spectra with the spectra observed in other main UHECRs observatories, does not change qualitatively our results. Interestingly, this extremely heavy composition at the source is comparable to the upper limit obtained using the angular distribution of these UHECRs. These ratios of $N_{Fe}(> 26E)/N_p(> E)$ are $> 0.072$ for the VCV catalogue and $> 0.084$ for correlations with Cen A.

Finally, we note that the spectral index, found here, is much harder than what observed in lower energies, $\alpha = 3$ [19]. This arises from the GZK attenuation affecting nuclei at these energies. Such hard spectra were obtained in detailed propagation simulations [16, 17, 20, 24].

We have shown that the PAO penetration depth measurements and the penetration depth numerical simulations yield a robust upper limit on the observed proton fraction of the UHECRs flux. This limit drops below 50% at energies higher than 10 EeV and below 30% at higher energies. These measurements are inconsistent with the composition of 75% protons and 24% He, that is common in the Universe and they require a significant fraction of intermediate mass nuclei.

The conversion of the observed composition to the composition at the source depends on the acceleration and propagation. Using a simple toy model we find that the protons to metals mass ratio at the source should be about 1 : 1. This metallicity is larger by a factor of a hundred than the solar metal abundance of $\approx 1\%$, which reflects typical metallicity in the Universe. This high metallically puts a new severe constraint on the sources, since objects dominated by nuclei heavier than He are rare in the astrophysical landscape.

Active galactic nuclei (AGNs) are natural UHECRs accelerators [23, 24]. Most AGNs can accelerate metals to $\sim 10^{20}$eV and protons to an order of magnitude lower. This would produce, naturally, the observed composition transition [14, 17] as well as the cutoff in the spectrum at higher energies [18]. However this would require a very heavy composition, whereas AGNs typically show solar-like metallicities [25].

Gamma ray bursts (GRBs) are another natural UHECRs accelerators (see however [27, 28]). If UHECRs are produced by GRBs' internal shocks, they are composed of the original material of the jets. One has to invoke, in this case, a very efficient nucleosynthesis within the jets and survival of the produced nuclei during the acceleration [20, 30]. It is not clear that this can be achieved generically. Recall that the UHECR output of GRBs should be comparable or larger than their $\gamma$-rays output. Alternatively if UHECRs are produced by external shocks they will be composed by the circum-burst winds surrounding the star. GRBs’ progenitors, Wolf-Rayet stars, have He, C and O dominated wind whose composition is too light.

A variation on this theme was proposed by Liu and

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5 Within this acceleration model the number of Fe nuclei accelerated to energies larger than 26E equals to $c_{Fe}/c_p$ times the number of protons accelerated to energies larger than E (Note that [22] use somewhat different notations)
Wang [31] who invoke, instead of regular GRBs, low-luminosity GRBs which they describe as “semi relativistic core collapse supernovae that involve an engine activity” and call “hypernovae”. These are also based on Wolf - Rayet progenitors. However, low-luminosity GRBs jets do not penetrate the stellar envelope and the observed emission is produced by a shock breakout [52]. Thus, it is not clear how could these bursts accelerate UHECRs in the first place. Furthermore, as sources of heavy UHECRs they suffer from all problems mentioned earlier concerning regular GRBs.

A rapidly rotating young pulsar with a strong but reasonable magnetic field (\(\sim 10^{13} \text{ G}\)) can accelerate Fe to UHECR energies [33]. Fang et al. [34] suggested that young pulsars are UHECR sources and the origin of the heavy composition is the Fe rich crust. However, X-ray observations of neutron stars suggest the existence of an atmosphere composed of proton and light elements above the crust (see [33] and citations therein). Acceleration of this atmospheric component will result in a light composition. This poses a serious doubt concerning this model.

Overall, while astrophysical heavy UHECRs sources cannot be ruled out with absolute certainty, the strict constraint on the composition obtained here (that constrain both the protonic and the He components) makes the UHECRs sources puzzle even harder to solve. In particular it rules out the most natural sources, AGNs. There is no single clear model that naturally produces UHECRs with such a composition. One may search for acceleration processes that are not rigidity dependent and favor heavy nuclei over light ones, however such a process is not readily available.

Given this situation one can consider the following alternatives to the heavy composition. First, the observational data might be incorrect or somehow dominated by poor statistics: these results are based on about 1500 events at the lowest energy bin and on only about 50 at the highest one. The possibility of a miscalculation in the shower simulations is unlikely. Different simulations [4][4] obtain comparable results. However, the simulations depend on the extrapolations of the proton’s cross section from the measured energies of a few TeV to the range of an UHECR - atmospheric nucleon collision, which are factor of 100 higher in energy. Is it possible that this extrapolation breaks down? A larger cross section than the one extrapolated can explain the shorter penetration depth. If so these findings might provide hints of a new physics that set in at energies of several dozen TeV [35].

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