

# Implications of cosmic ray results for UHE neutrinos

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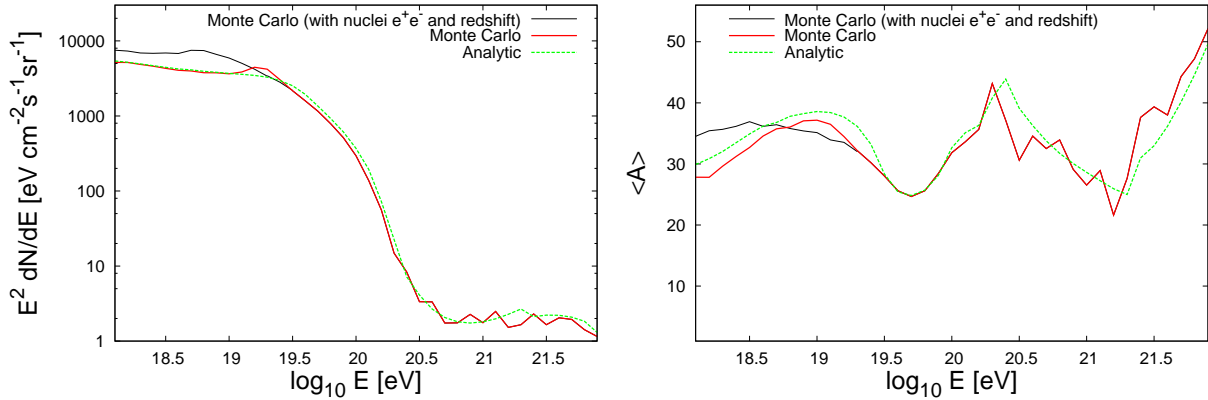
**Abstract.** Recent measurements of the spectrum and composition of ultrahigh energy cosmic rays suggest that their extragalactic sources may be accelerating heavy nuclei in addition to protons. This can suppress the cosmogenic neutrino flux relative to the usual expectation for an all-proton composition. Cosmic neutrino detectors may therefore need to be even larger than currently planned but conversely they will also be able to provide valuable information concerning astrophysical accelerators. Moreover measurement of ultrahigh energy cosmic neutrino interactions can provide a unique probe of QCD dynamics at high parton density.

## 1. Introduction

Cosmic rays have been detected with energies up to  $\sim 3 \times 10^{20}$  eV. Ultra high energy neutrinos *must* also be generated during their interactions with ambient matter and radiation in the sources, and with intergalactic radiation backgrounds during their propagation to Earth [1]. The detection of these neutrinos would enable unambiguous identification of the sources, as well as probe new physics both in and beyond the Standard Model [2].

In order to estimate the expected event rates in cosmic neutrino detectors such as ANITA [3], HiRes [4], IceCube [5], and the Pierre Auger Observatory [6], it is thus essential to take new data on ultra high energy cosmic rays (UHECRs) into account. There has been significant recent progress in the field, in particular HiRes [7] and Auger [8] have established that the energy spectrum is attenuated beyond  $\sim 5 \times 10^{19}$  eV. This is indeed as expected if the primaries are protons undergoing photopion interactions on the cosmic microwave background (CMB) [9, 10]. Such interactions should also give rise to a flux of high energy neutrinos [11] and this “guaranteed cosmogenic flux” is a prime target for cosmic neutrino detectors. A somewhat higher (but more model-dependent) flux of neutrinos should also be generated in the sources of the cosmic rays through  $pp$  and  $p\gamma$  interactions [12].

However it is not clear that the UHECRs are necessarily protons. Astrophysical accelerators are expected to generate particles up to a maximum energy which is proportional to their charge [13] hence it would be less challenging for plausible sources such as active galactic nuclei (AGN) to emit  $\sim 10^{20}$  eV iron nuclei rather than protons. The correlation observed by Auger between the arrival directions of UHECRs above  $6 \times 10^{19}$  eV and AGN within 75 Mpc [14] would seem to argue against heavy nuclei as primaries since these ought to be significantly deflected by intergalactic and galactic magnetic fields. However UHECR nuclei will undergo photodisintegration on the cosmic infrared background (CIB) with a energy loss length similar to protons [15] so the cosmic rays arriving at Earth will be much lighter, thus reducing the impact of magnetic fields especially in the Galaxy. Moreover intergalactic magnetic fields may be weaker than is usually assumed — observationally only upper limits are known.



**Figure 1.** The energy spectrum (left) and average composition (right) at Earth calculated using both analytic and Monte Carlo techniques, for the case of iron nuclei injected by homogeneously distributed sources with  $dN/dE \propto E^{-2}$  up to a maximum energy of  $10^{22}$  eV [28].

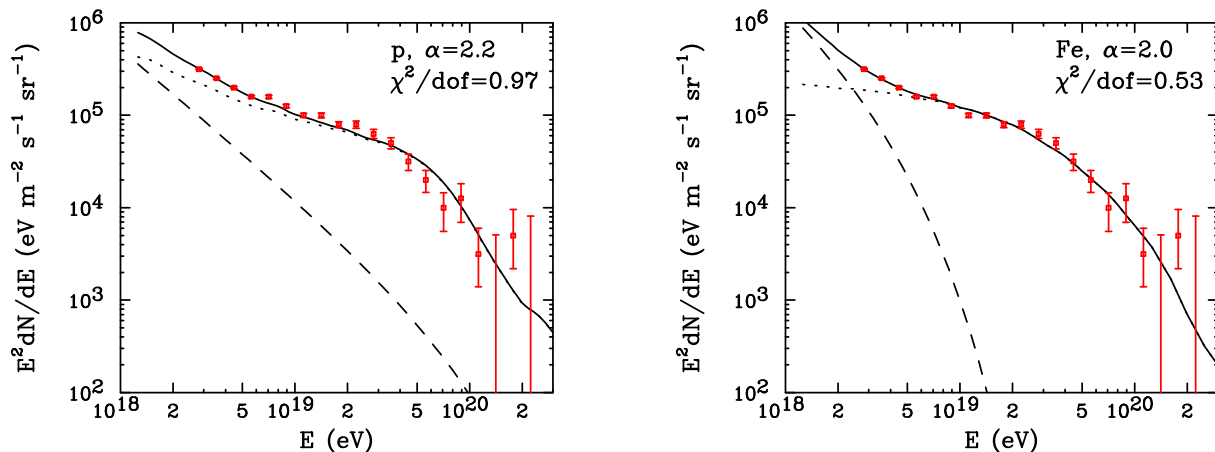
The chemical composition of UHECRs can in principle be inferred from the development of the air showers they trigger on hitting the Earth's atmosphere. For a given energy, the depth at which the shower reaches maximum development,  $X_{\max}$ , is smaller for heavy nuclei than for protons, and its average value increases logarithmically with energy. There is however considerable scatter due to fluctuations associated with the stochasticity of the first interaction and moreover different (semi-empirical) simulation codes for air showers make differing predictions for  $X_{\max}$  [16]. Earlier data from HiRes had suggested that the composition becomes light in the range  $\sim 10^{18} - 3 \times 10^{19}$  eV [17]. However recent measurements by Auger [18] which reach somewhat higher in energy indicate a gradual *decrease* in  $X_{\max}$  above  $\sim 2 \times 10^{18}$  eV, implying increasing dominance by heavy nuclei. This would argue against the interpretation of the 'ankle' in the energy spectrum at  $\sim 10^{19}$  eV as due to  $e^+e^-$  energy losses of extragalactic cosmic ray *protons* on the CMB [19]. The alternative explanation is that at this energy the flatter spectrum of extragalactic cosmic rays dominates over the falling galactic component, whereas in the former case the transition must occur at a lower energy of  $\sim 10^{18}$  eV ('second ankle') and require fine-tuning between the two components to ensure a smooth transition.

Hence it is necessary to determine the range of possible compositions for the primary particles which is consistent with the energy spectrum and  $X_{\max}$  measured at Earth. To do this we must compute the propagation of UHECR nuclei through the CIB to match our understanding of the propagation of UHECR protons through the CMB and the generation of the cosmogenic neutrino flux [20, 21]. Nuclei would undergo photodisintegration (at a lower energy threshold than that for pion production) and the secondary nucleons, if still sufficiently energetic would then produce pions through the usual GZK process, also the neutrinos would undergo  $\beta$ -decay. Depending on the choice of chemical composition and injected spectrum of the UHECRs, the cosmogenic neutrino spectrum can in some cases be considerably suppressed relative to that predicted for an all-proton composition.

## 2. The cosmogenic neutrino flux

The complex process of the photodisintegration of UHECR nuclei into lighter nuclei and nucleons has been addressed using Monte Carlo techniques by several authors [22, 23, 24, 25, 26, 27], but it is useful to develop an *analytic* description of this phenomenon [28].

This has turned out to be very successful, e.g. Figure 1 shows a comparison of our analytic [28] and Monte Carlo [23, 26] results for the case when iron nuclei are injected by the sources.



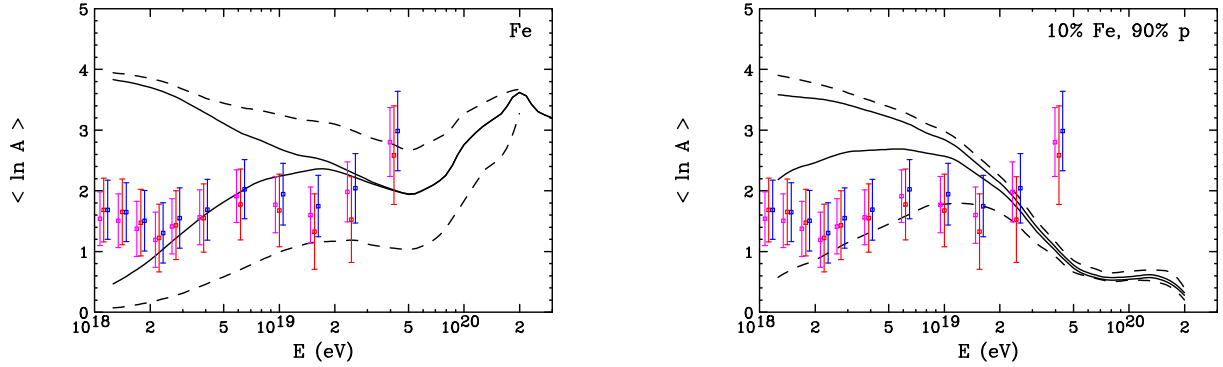
**Figure 2.** The best fit spectrum for an all-proton and all-iron UHECR composition with injection power-law slopes of -2.2 and -2.0 respectively — the dotted, dashed and solid lines denote the assumed extragalactic, galactic and combined components [27].

This both validates and provides valuable insights into the Monte Carlo results. Given the uncertainties concerning the galactic-extragalactic transition (and the composition of the galactic component), we find that the Auger data concerning the energy spectrum [8] as well as the composition at Earth [18] can be satisfactorily fitted with a wide range of nuclei being injected, as is illustrated in Figures 2 and 3 [27].

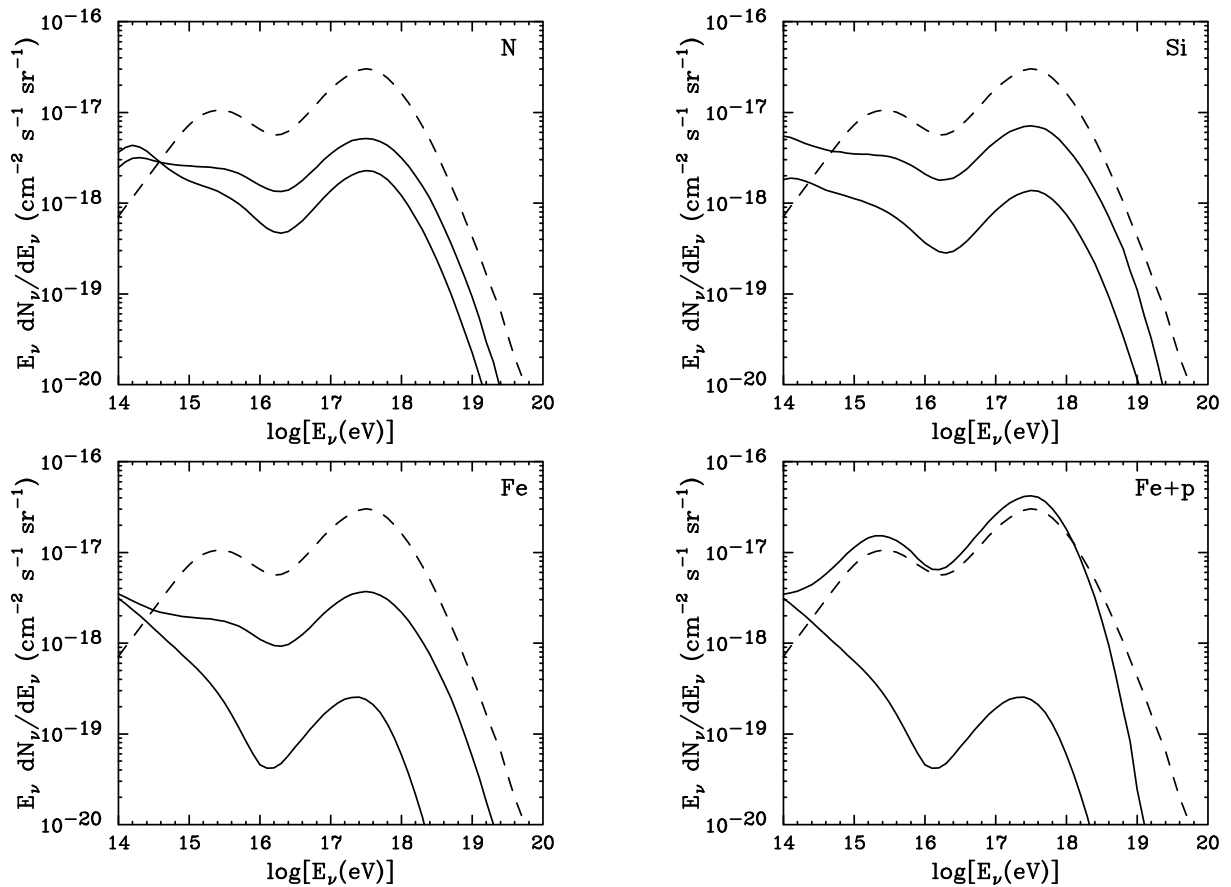
The corresponding cosmogenic neutrino flux is however very different and can be suppressed significantly relative to the all-proton case. However as shown in Figure 3, the data is also consistent with a proton-dominated spectrum with a small admixture of heavy nuclei, in which case the cosmogenic flux will still yield of  $\mathcal{O}(1)$  cosmogenic neutrino event per year in a kilometer-scale neutrino telescope. With a bigger detector, it may even be possible to constrain the composition at injection and the free parameters in the calculation, e.g. the spectral slope and maximum energy to which particles are accelerated as well as possible evolution of the number density of sources with redshift which we have not considered here. Note that while the observed UHECRs cannot come from very far away because of the GZK energy losses, the universe remains transparent even to such high energy neutrinos back to the recombination epoch.

### 3. Neutrinos from cosmic ray accelerators

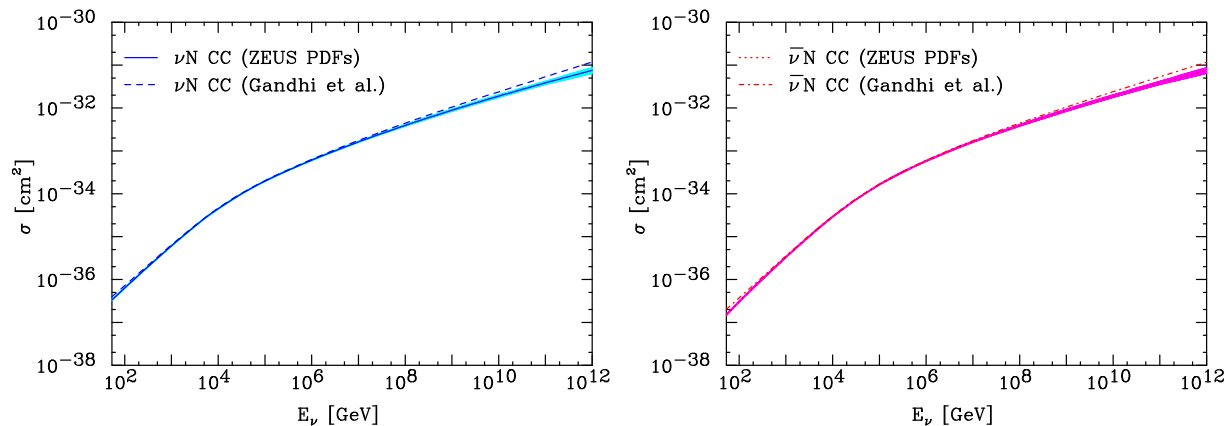
The neutrino flux expected from the extragalactic sources of cosmic rays depends on how the particles are accelerated and the environment in which this occurs. Assuming that the sources are ‘optically thin’ and normalising to the observed UHECR spectrum, an upper limit can be placed on the diffuse flux [12] which is only a little higher than a plausible estimate for the actual flux based on the known efficiency of  $pp$  and  $p\gamma$  interactions for producing neutrinos. This estimate is of course significantly higher in the ‘low cross-over’ model for the galactic–extragalactic transition since the sources must then put much more power into generating cosmic rays [29]. Of course just like the cosmogenic flux, all such estimates are sensitive to the assumed composition at injection. We find that based on what is observationally known about the environment in suggested sources, heavy nuclei are likely to be completely photodissociated in  $\gamma$ -ray bursts but survive unscathed in starburst galaxies, while the situation in AGN is somewhere in-between [30]. With regard to individual objects, the detection of correlations between UHECR arrival directions and nearby AGN has inspired many estimates of the expected neutrino flux, e.g. *Centaurus A* may yield 0.4 – 0.6 events/yr in IceCube [31]



**Figure 3.** The composition at Earth when pure iron nuclei (left) or a mixture of protons and iron nuclei (right) are injected by the sources, if we require that after propagation the measured energy spectrum at Earth is consistent with the Auger data — the broadening below  $\sim 10^{19}$  eV results from possible variations in the composition of the galactic component while the dashed lines denote the 95% c.l. range. The data points correspond to the  $X_{\max}$  measurements by Auger interpreted according three different hadronic physics models: EPOS 1.6 (magenta), QGSJET-III (red) and SIBYLL 2.1 (blue), including systematic and statistical errors [27].



**Figure 4.** The range of cosmogenic neutrino spectra for various injected chemical species which, after propagation, are consistent with the Auger spectrum and  $X_{\max}$  measurements; the dashed curve is for an all-proton spectrum with power-law slope  $\alpha = -2.2$  and  $E_{\max} = 10^{22}$  eV [27].



**Figure 5.** The total charge-current cross-section at ultra high energies for neutrinos and antineutrinos along with the  $\pm 1\sigma$  uncertainties (shaded band) [33].

#### 4. Neutrino interaction cross-sections

To estimate detection rates for UHE neutrinos we also need to know the cross-section for their scattering on nucleons, at energies far beyond those achievable at terrestrial accelerators. In the framework of the quark-parton model, such (deep inelastic) scattering accesses very large values of  $Q^2$ , the invariant mass of the exchanged vector boson, and very small values of Bjorken  $x$ , the fraction of the the incoming nucleon momentum taken by the struck quark. Thus we need to extrapolate the experimentally measured parton distribution functions (PDFs) of the nucleon to the relevant kinematic range using the DGLAP formalism of perturbative QCD. This is best done using up to date information from the experiments at HERA, which have accessed the lowest  $x$  and highest  $Q^2$  scales to date. We have used the ZEUS-S global PDF fits [32], updated to include all the HERA-I data, at next-to-leading-order and with corrections for heavy quark thresholds — the results [33] are shown in Fig.5 along with earlier values [34] which were calculated at leading order and using PDFs which no longer fit modern data. We also provide a measure of the uncertainties which derive mainly from the correlated systematic errors of the input data sets. These updated cross-sections have been used in recent Auger analyses [35] and are being incorporated into ANIS, the MC event generator for neutrino telescopes [36].

There are additional theoretical uncertainties at very high energies ( $> 10^8$  GeV) since at the very low- $x$  values probed the gluon density is rising rapidly so it is probably necessary to go beyond the DGLAP formalism in order to sum  $\ln(1/x)$  diagrams, as in the BFKL formalism. An alternative approach is to consider non-linear terms which describe gluon recombination as in the ‘colour glass condensate’ model which has had considerable success in explaining RHIC data. These non-perturbative effects can *reduce* the cross-section at high energies by a factor of  $\sim 2 - 10$ . Whether this is indeed the case can in principle be tested by measuring the zenith angle dependence of the cosmic UHE neutrino flux. For example in an air shower array like Auger, the rate of quasi-horizontal events due to neutrinos interacting in the atmosphere is proportional to the cross-section, but the rate of Earth-skimming events due to tau neutrinos interacting in the Earth’s crust is approximately independent of the cross-section, so their ratio provides a diagnostic [37]. However the expected low event rates would require much larger detection volumes than are presently available e.g. a satellite-borne fluorescence detector like EUSO has been considered [38]. Proposed extensions of Cherenkov detectors like IceCube using radio detection techniques also seem very promising in this regard.

## 5. Conclusions

Ultrahigh energy cosmic neutrinos have not yet been detected but there is no doubt that they exist in Nature and after years of effort experiments are approaching the sensitivity at which the “guaranteed cosmogenic flux” should be seen. It has long been recognised that this would open up a new astronomy and be a decisive step towards identifying the sources of cosmic rays. It may also be possible using this free UHE beam of neutrinos to discover new physics both in and beyond the Standard Model. This is a fertile ground for the meeting of astrophysics and particle physics and the future indeed looks bright.

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