The Impact of Heavy Nuclei on the Cosmogenic Neutrino Flux

Dan Hooper\textsuperscript{1}, Andrew Taylor\textsuperscript{1} and Subir Sarkar\textsuperscript{2}

\textsuperscript{1}Astrophysics, University of Oxford, Oxford OX1 3RH, UK
\textsuperscript{2}Theoretical Physics, University of Oxford, Oxford OX1 3NP, UK

hooper@astro.ox.ac.uk, amt@astro.ox.ac.uk, sarkar@thphys.ox.ac.uk

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Abstract

As ultra-high energy cosmic ray protons propagate through the universe, they undergo photo-meson interactions with the cosmic microwave background, generating the ‘cosmogenic’ neutrino flux. If, however, a substantial fraction of the cosmic ray primaries are heavy nuclei rather than protons, they would preferentially lose energy through photo-disintegration so the corresponding neutrino flux may be substantially depleted. We investigate this issue using a Monte Carlo simulation of cosmic ray propagation through intergalactic radiation fields and assess the impact of the altered neutrino fluxes on next-generation neutrino telescopes.
1 Introduction

The origin of the highest energy cosmic rays is among the most interesting puzzles of modern astrophysics and may hold clues to new fundamental physics [1, 2]. Both air shower and atmospheric fluorescence experiments have detected ultra-high energy cosmic rays (UHECRs) with energies up to and beyond $10^{20}$ eV [3, 4, 5, 6]. If these are protons, then their energies are well above the predicted ‘GZK cutoff’ [7, 8]. Additionally, their sky distribution is isotropic and their arrival directions do not correlate with any plausible nearby sources. This has prompted many speculative models involving new physics, e.g. decaying superheavy dark matter in the Galactic halo [9, 10]. Alternatively, the UHECRs may be produced in the local interactions of particles such as neutrinos which can travel cosmological distances without interacting with the cosmic microwave background (CMB) — the ‘Z-burst’ mechanism [11, 12]. Even more exotic possibilities have been considered, for example the violation of Lorentz invariance at very high energies [13, 14].

Astrophysical solutions to this problem may also be viable. A relatively local source could, in principle, be responsible for the highest energy events observed (although no plausible sources have been identified [2]) and the isotropic distribution may be due to larger than expected intergalactic magnetic fields. Alternatively, a substantial quantity of heavy nuclei (rather than only protons) may be accelerated in the cosmic ray sources. Heavy nuclei, with their higher electric charge hence smaller rigidity, would be more strongly deflected by magnetic fields and thus would be more likely to appear as an isotropic distribution of events. Additionally, heavy nuclei propagate over cosmological distances differently than protons, raising the possibility that they could originate from more distant sources [15]. Moreover, due to their higher electric charge, the ‘Hillas criterion’ for the acceleration of heavy nuclei is relaxed relative to protons [1].

Experiments studying UHECRs have limited ability to measure their composition through comparison of the characteristics of the air showers with Monte Carlo simulations based on empirical hadronic interaction models [16]. Data from Fly’s Eye suggested a gradual transition from heavy primaries at $\sim 3 \times 10^{17}$ eV to proton domination at $\sim 10^{19}$ eV [17]. Its successor, HiRes, reported a similar result [18]. Although this is consistent with the indication from Haverah Park data that less than 30% of cosmic rays above $\sim 10^{19}$ eV are iron nuclei [19], in the energy range $\sim 2 \times 10^{17} - 10^{18}$ eV, iron nuclei are found to dominate 2 to 1 [20]. This is also indicated by a recent reanalysis of Volcano Ranch data in the energy range $\sim 5 \times 10^{17} - 10^{19}$ eV [21]. Moreover, it has been argued that the highest energy Fly’s Eye event at $\sim 3 \times 10^{20}$ eV could have been a heavy nucleus [22, 23].

It has been noted that the interactions of UHE protons propagating over cosmological distances should generate a flux of neutrinos [24, 25, 26] and much effort has been devoted to calculating this ‘cosmogenic’ neutrino flux [27, 28]. This is often thought of as a “guaranteed” source of UHE neutrinos, expected to be detectable in the next generation of experiments such as IceCube [29], Auger [30] and Anita [31]. It is clearly important to determine how much this flux would be altered if the cosmic ray spectrum contains a substantial fraction of heavy nuclei.
2 Propagation of Ultra-High Energy Protons and Heavy Nuclei

To study UHE heavy nuclei propagation, we have constructed a Monte Carlo program to model the relevant interactions. Our simulation includes the continuous energy losses associated with pair production and the adiabatic expansion of the universe, as well as the key stochastic processes — photo-meson interactions of nucleons and photo-disintegration of heavy nuclei.

At very high energies, protons interact with the CMB producing electron-positron pairs, \( p + \gamma_{\text{CMB}} \rightarrow p + e^+ + e^- \). The energy loss rate for this process climbs rapidly until a few times \( 10^{19} \) eV where it reaches its maximum. The pair production energy loss length in the range \( 10^{19} - 10^{20} \) eV is a few hundred Mpc [32]. This process can safely be treated as continuous for our purposes.

The situation is somewhat different for heavy nuclei. The energy loss rate due to pair production is proportional to the charge of the nucleus squared, and thus can be considerably more rapid. The threshold energy for this process is also higher, however, e.g. the energy loss rate for iron nuclei peaks above \( 10^{21} \) eV, much higher than for protons [32].

More important for our purposes than energy losses due to pair production are the effects of photo-meson interactions and photo-disintegration. At these energies, processes such as \( p + \gamma_{\text{CMB}} \rightarrow p + \pi^0 \) and \( p + \gamma_{\text{CMB}} \rightarrow n + \pi^+ \) can take place via the exchange of a \( \Delta \)-hadron near resonance (1.232 GeV center-of-mass energy). The cross-sections for these processes are very large, leading to energy loss lengths of tens of Mpc for protons above a few times \( 10^{19} \) eV. It is this effect that is expected to produce the GZK cutoff in the cosmic ray spectrum [7, 8].

Whereas the most important energy loss process for protons is the photo-production of pions, for ultra-high energy heavy nuclei, it is the process of photo-disintegration which has a much lower threshold [33, 15]. Here the nucleus interacts with a background photon causing it to break up into a lighter nucleus or nuclei along with a (typically) small number of protons and/or neutrons. In part of the energy range we are interested in, the dominant opacity for this comes from scattering of heavy nuclei on the cosmic infra-red background (CIB) rather than on the CMB. However, in contrast to the latter, the spectrum of the CIB is not well measured, leading to considerable uncertainties in the propagation of heavy nuclei. The cross-sections for N-nucleon emission for a given nucleus have been experimentally measured in the energy range we are interested in and we use the parameterizations given in Ref. [34].

3 The Generation of Cosmogenic Neutrinos

When the UHE primaries are protons, the main source of cosmogenic neutrinos are charged pions produced in photo-meson interactions. These decay as \( \pi^+ \rightarrow \mu^+\nu_\mu \rightarrow e^+\nu_e\bar{\nu}_\mu \nu_\mu \), providing a rich source of neutrinos at EeV energies. Neutrons are created through \( p + \gamma_{\text{CMB}} \rightarrow n + \pi^+ \) and their decays generate more neutrinos, \( n \rightarrow p^+ + e^- + \bar{\nu}_e \). The energy of these neutrinos is considerably smaller, however, producing a secondary flux peaking in the PeV range.

To calculate the cosmogenic neutrino spectrum, the injection spectrum of protons (or heavy nuclei) and the cosmological distribution of sources need to be specified. To enable comparison with previous work [35], we adopt the popular parameterizations [36]:

\[
\frac{dN_p}{dE_p} \propto E_p^{-2} \exp \left[ -\frac{E_p}{10^{21.5} \text{eV}} \right],
\]  

(1)

Figure 1: The cosmogenic neutrino (plus anti-neutrino) flux produced in the propagation of ultra-high energy protons (histogram). The solid curve shows a previous result \cite{27} for comparison.

\begin{equation}
H(z) = \begin{cases} 
(1 + z)^3 & \text{for } z < 1.9, \\
(1 + 1.9)^3 & \text{for } 1.9 < z < 2.7, \\
(1 + 1.9)^3 \times e^{(2.7 - z)/2.7} & \text{for } z > 2.7,
\end{cases}
\end{equation}

for the cosmic ray injection spectrum and source distribution, respectively. With these choices, we use our Monte Carlo to calculate the cosmogenic neutrino flux for proton primaries shown in Figure 1. We find reasonable agreement with the previous calculation made using the same injection spectrum and source distribution, but with a more sophisticated treatment of photomeson interactions \cite{27}. For further details concerning the interactions UHE protons undergo during propagation, we direct the reader to Ref. \cite{35}.

The neutrino flux produced in the propagation of heavy nuclei can be quite different from the result shown in Figure 1. As nucleons are broken off from a heavy nucleus, the Lorentz factor is unchanged so their energy is smaller by a factor of the nuclear mass number, $A$, than the energy of the primary cosmic ray. Therefore, considerably more energetic heavy nuclei are required to produce neutrinos via charged pion decay. For iron nuclei ($A = 56$), energies of $\sim 2 \times 10^{21}$ eV or higher are needed to produce neutrinos by this mechanism. Given the much smaller flux injected at such high energies, the neutrino flux from charged pion production can be considerably depleted if heavy nuclei make up a substantial fraction of the ultra-high energy cosmic rays. It is easy to see that for a differential $E^{-2}$ spectrum, the result in Figure 1 represents an upper bound on the EeV neutrino flux from pion decays if the primaries are heavy nuclei.
The same is not true for neutrinos produced in neutron decays. As heavy nuclei propagate and undergo photo-disintegration, both protons and neutrons are removed and the neutrons decay producing neutrinos as described earlier. Thus for each heavy nucleus, it is possible to generate up to 3 neutrinos per neutron \( (A - Z) \), e.g. up to 90 neutrinos for each iron nucleus. In practice, many nuclei do not fully disintegrate, however, and thus generate fewer neutrinos than might be expected through this process.

The rate at which heavy nuclei photo-disintegrate depends strongly on the density of CIB photons. Given the large observational uncertainties in the CIB fluxes, this can lead to ambiguities regarding the propagation of heavy nuclei. In particular, it is difficult to predict the shape of the propagated cosmic ray spectrum at Earth for heavy nuclei primaries with much confidence. This introduces some uncertainty in the normalization of the primary spectrum.

As described earlier, the neutrino spectrum in Figure 1 is produced by two mechanisms — charged pion and neutron decay, corresponding to the higher and lower energy peaks, respectively. For UHE heavy nuclei to produce neutrinos in the higher energy peak, the protons created by their photo-disintegration must have energies above the GZK cutoff. This requires a nucleus with an energy of roughly \( A \times 4 \times 10^{19} \) eV (alternatively, a Lorentz factor of a few times \( 10^{10} \)). For such energetic nuclei, interactions with the CMB, and not the CIB, dominate [33]. Only at lower energies, where interactions produce sub-GZK protons, does the CIB provide the main target.

Thus the neutrino flux populating the higher energy peak does not depend directly on the assumed CIB spectrum although there is an indirect effect because the propagated cosmic ray spectrum has to be correctly normalized. The lower energy peak does, however, depend directly on the intensity of the CIB. Heavy nuclei with energy around \( A \times 10^{19} \) eV or lower begin to photo-disintegrate due to interactions with CIB photons, producing neutrons which decay generating neutrinos in the lower energy peak. However this lower energy population of neutrinos is considerably more difficult to detect experimentally due to the much larger backgrounds. For this reason, we will focus our attention primarily on the neutrinos generated in the decay of charged pions and will not be overly concerned with the debates regarding the intensity of the CIB. We adopt the spectrum proposed in Ref. [37], which is broadly consistent with TeV \( \gamma \)-ray observations of active galactic nuclei. If we use instead the compilation of direct measurements of the CIB [38], the neutrino fluxes in both peaks increase by a factor of \( \sim 2 \). Given that some of these CIB measurements may be contaminated and thus represent upper bounds to the cosmic flux, we do not pursue this issue further.

4 Results

The cosmogenic neutrino fluxes for iron, oxygen and helium primaries are shown in Figure 2 along with the result for protons for comparison. The curves have been normalized by matching the proton plus heavy nuclei flux to the observed cosmic ray spectrum at \( 3 \times 10^{19} \) eV [1]; this ensures that at higher energies, the energy spectrum at Earth is bounded between the results announced by AGASA [5] and by HiRes [6]. As expected, the higher energy population of neutrinos (produced in charged pion decay) is depleted for heavy nuclei, while the lower energy population of neutrinos (produced in neutron decay) is enhanced. Unfortunately, the lower energy population is considerably more difficult to detect experimentally (see §5).

These results depend on the assumptions made. In particular, the neutrino spectrum can be
considerably different if the observed UHECRs come from a small number of powerful, nearby sources, rather than the cosmologically distant distribution of Eq. (2). The choice of injection spectrum also plays an important role. We have assumed the flattest possible power-law spectrum with an exponential cutoff imposed at $10^{21.5}$ eV. If the spectrum were to extend to higher energies, more heavy nuclei would photo-disintegrate to yield protons above the GZK cutoff and, hence more EeV-scale neutrinos would be produced. In Figure 3 we show that the flux is boosted by about a factor of 3 if the cutoff is shifted upwards by a factor of 10.

5 Event Rates in Next Generation Neutrino Experiments

UHE neutrinos of cosmic origin have not yet been experimentally detected but there are general expectations for significant fluxes from various astrophysical and cosmological sources [39]. Several innovative experiments are currently being developed with the sensitivity required to observe cosmogenic neutrinos within the next few years — these include IceCube, Auger and Anita.

IceCube, presently under construction at the South Pole, will be the first km-scale neutrino telescope. It will be capable of observing both muon tracks produced in charged current muon neutrino interactions and shower events produced in charged and neutral current events. Although optimized for the energy range of $10^{11} - 10^{18}$ eV [29], IceCube will be sensitive to neutrino energies up to $\sim 10^{20}$ eV [40].
Figure 3: The neutrino spectrum produced in the propagation of $^{56}$Fe nuclei. The dotted blue histogram results from the injection spectrum of Eq. (1), which has an exponential cutoff at $10^{21.5}$ eV while the solid black histogram has the cutoff extended to $10^{22.5}$ eV.

The Pierre Auger Observatory, designed primarily to study the UHE cosmic ray spectrum, will also be sensitive to UHE neutrinos. With their much smaller interaction cross-sections, neutrinos would interact well within the atmosphere and thus be identified as ‘deeply penetrating, quasi-horizontal showers’. Earth-skimming tau neutrinos would also provide distinctive detection signatures in Auger [30].

The Anita experiment will be flown on balloons around the South Pole using radio antennae to detect the interactions of UHE Earth-skimming neutrinos in the polar icecap [31].

Despite the very different techniques used by these experiments, all three expect similar sensitivities to UHE neutrinos, in neighbouring energy bands. About 1 UHE neutrino event per year is expected in either IceCube or Auger given the cosmogenic neutrino flux of Ref. [27], with a similar number expected in a 10-day Anita flight. Given this, it is unrealistic to expect any of these experiments to measure the cosmogenic neutrino spectrum in detail. Due to the very low background at EeV energies, however, only a small number of events is required to achieve a definite detection.

For concreteness, we have focused on the IceCube experiment and the expected event rates are shown in Table 1. It is clear from these numbers that substantial heavy nuclei content in the UHECR spectrum can sharply reduce the ability of neutrino telescopes to observe the cosmogenic neutrino flux. To improve on the sensitivity of present experiments, new detection techniques may be required. This might include extensions of IceCube [41], space based air shower experiments such as EUSO [42], acoustic detection technology [43], or an experiment such as SALSA [44].
|                | Showers | Muons ($E_{\mu}^{\text{thr}} = 1$ PeV) | Muons ($E_{\mu}^{\text{thr}} = 10$ TeV) |
|----------------|---------|----------------------------------------|----------------------------------------|
| Protons ($A = 1$) | 0.57    | 0.72                                   | 1.16                                   |
| Helium ($A = 4$)  | 0.42    | 0.50                                   | 0.80                                   |
| Oxygen ($A = 16$) | 0.19    | 0.23                                   | 0.73                                   |
| Iron ($A = 56$)   | 0.036   | 0.042                                  | 0.17                                   |

Table 1: The expected cosmogenic neutrino-induced event rates per year in IceCube, from the propagation of UHE protons and heavy nuclei which generate the neutrino fluxes shown in Figure 2. Rates are shown for both shower and muon events. For the former, a 1 PeV shower energy threshold was imposed, while for the latter muon energy thresholds of both 10 TeV and 1 PeV were considered.

Note in Table 1 that lowering the muon threshold of a detector from 1 PeV to 10 TeV results in only a fairly mild change in the predicted event rate. Both the neutrino-nucleon cross-section and the energy loss distance of muons in ice or water decrease with energy, making neutrino telescopes considerably more efficient at higher energies. Furthermore, the atmospheric neutrino background rapidly falls off in this energy range. After the consideration of these features, we conclude that, even in the case of iron nuclei, the lower energy peak of Figures 2 and 3 will not be observable in any planned experiment.

6 Conclusions

If the UHE cosmic rays are protons, the spectrum of neutrinos produced during their propagation over cosmological distances is expected to be detectable in next-generation experiments. However, if the highest energy cosmic rays are heavy nuclei, this neutrino flux may be substantially depleted. For relatively light nuclei, e.g. $^4$He, the suppression is only by about 50%, but for heavier nuclei such as $^{16}$O or $^{56}$Fe, the cosmogenic neutrino flux is reduced by a factor of between 3 and 15. The reduction would be less severe if the UHE cosmic ray spectrum extends beyond ZeV energies without attenuation. Also of course the reduction would be at most by a factor of 3, if a third of the UHE cosmic ray primaries are in fact protons.

Such a reduction in the cosmogenic neutrino flux would naturally make experimental detection more difficult. On the other hand, a detection of EeV neutrinos in experiments such as IceCube, Auger and Anita would provide a complementary probe of the composition of UHE cosmic rays. Alternatively if these experiments detect much larger UHE neutrino fluxes than expected from the intergalactic propagation of cosmic rays, then this would implicate local sources of UHECRs such as decaying dark matter in the Galactic halo [10, 15, 36].

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