FERMILAB-PUB-07-454-A

Predictions for the Cosmogenic Neutrino Flux in Light of New Data from the Pierre Auger Observatory

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The Pierre Auger Observatory (PAO) has measured the spectrum and composition of the ultrahigh energy cosmic rays with unprecedented precision. We use these measurements to constrain their spectrum and composition as injected from their sources and, in turn, use these results to estimate the spectrum of cosmogenic neutrinos generated in their propagation through intergalactic space. We find that the PAO spectrum and elongation rate measurements can be well fitted if the injected cosmic rays consist entirely of nuclei with masses in the intermediate (carbon, nitrogen or oxygen) to heavy (iron, silicon) range. A mixture of protons and heavier species is also acceptable but (on the basis of existing hadronic interaction models) injection of pure light nuclei (protons, helium) results in unacceptable fits to the new elongation rate data. The expected spectrum of cosmogenic neutrinos can vary considerably, depending on the precise spectrum and chemical composition injected from the cosmic ray sources. In the models where heavy nuclei dominate the cosmic ray spectrum and few dissociated protons exceed GZK energies, the cosmogenic neutrino flux can be suppressed by up to two orders of magnitude relative to the all-proton prediction, making its detection beyond the reach of current and planned neutrino telescopes. Other models consistent with the data, however, are proton-dominated with only a small (1-10%) admixture of heavy nuclei and predict an associated cosmogenic flux within the reach of upcoming experiments. Thus a detection or non-detection of cosmogenic neutrinos can assist in discriminating between these possibilities.

PACS numbers: 98.70.Sa, 95.85.Ry

I. INTRODUCTION

The Pierre Auger Observatory (PAO) [1] has been designed to study ultrahigh energy cosmic rays (UHECRs) with energies above about 10^{18} eV, with the aim of uncovering their origin and nature. Such events are too rare to be detected directly, but the direction, energy and (to some extent) the chemical composition of primary particles can be inferred from the cascade of secondary particles induced when the primary impinges upon the upper atmosphere. These cascades, or air showers, have been studied by measuring the fluorescence light they produce in the atmosphere and by directly sampling shower particles at ground level. The PAO is a hybrid detector, exploiting both of these well established techniques by employing an array of water Čerenkov detectors overlooked by fluorescence telescopes. On clear and dark nights, air showers are simultaneously observed by both types of detectors, facilitating powerful reconstruction methods and control of the systematic errors which have plagued previous cosmic ray experiments.

The chemical composition of the UHECRs has long been a subject of debate. On the one hand, there are both theoretical and observational motivations for favoring a cosmic ray spectrum dominated by heavy or intermediate mass nuclei at the highest energies. In particular, according to the Hillas criterion [2], plausible astrophysical sources are able to accelerate particles to a maximum energy proportional to their charge. It is, therefore, rather less challenging for cosmic ray accelerators to generate $\sim 10^{20}$ eV iron nuclei than protons, for example. Furthermore, the lack of observed point sources suggests that there are either a very large number of faint cosmic ray sources, or that these particles are significantly deflected by large-scale magnetic fields. Since this deflection is most efficient for particles with large atomic number (electric charge), nuclei are again favored. On the other hand, it has been argued that the "dip" observed around $\sim 10^{19}$ eV in the UHECR spectrum is a signature of protons interacting with cosmic microwave background photons via electron-positron pair production [3].

To identify the species of primary UHECRs, one has to study the development of the resulting showers in detail. Essentially, at a given energy, showers initiated by heavy nuclei develop earlier in the atmosphere than proton-induced showers. This, however, is complicated by fluctuations associated with the stochasticity of the first interaction [4]. On average, proton-induced showers reach their maximum development deeper in the atmosphere, i.e. at a larger cumulated grammage, $X_{\max}$. Furthermore, $X_{\max}$ increases with energy, as more energetic showers can develop longer before being quenched by atmospheric losses. The way the average depth of maximum, $\langle X_{\max}\rangle$, varies with energy depends on the primary composition and particle interactions according to $\langle X_{\max}\rangle = D_e \ln(E/E_0)$, where D_e is the elongation rate and E_0 is a characteristic energy that depends on the primary composition [5]. Since $\langle X_{\max}\rangle$ and D_e can be determined from the longitudinal shower profile as measured with a fluorescence detector, E_0 and thus the composition can be extracted after estimating the energy from the total fluorescence yield.

The latest results from the PAO were presented recently at the 30th International Cosmic Ray Conference [6, 7, 8, 9]. Even though the observatory will not be completed until the end of 2007, it has already become the preeminent source of UHECR data. For example, $X_{\max}$ measurements [7] at extremely high energies ($E_{\rm CR} \gtrsim 10^{19.3}$ eV) are significantly more precise (uncertainties smaller by a factor of approximately 4) than the best measurements from the HiRes experiment [10].

The chemical composition of the highest energy cosmic rays has important implications to the the field of high and ultrahigh energy neutrino astronomy. Protons with an energy above a few times 10^{19} eV interact efficiently with the cosmic microwave and infrared background photons [11], producing pions which decay to generate a spectrum of ultrahigh energy neutrinos, known as the cosmogneic neutrino flux [12]. Cosmogenic neutrinos have often been thought of as an essentially guaranteed flux of ultrahigh energy neutrinos, likely within the reach of current and next generation neutrino detectors such as IceCube [13] and ANITA [14], as well as detectors such as the PAO itself [15]. This conclusion can be altered, however, if a substantial fraction of the UHECR spectrum consists of heavy or intermediate mass nuclei rather than protons [16]. Cosmic ray nuclei, in contrast to protons, generate ultrahigh energy neutrinos through photodisintegration followed by pion production through nucleon-photon scattering. 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.

In this paper, we consider the recent spectrum and elongation rate measurements from the PAO and use these results to constrain the spectrum and chemical composition of UHECRs at their sources. We then turn our attention to the cosmogenic neutrino spectrum which is generated through the interaction of these particles with the cosmic microwave and infrared backgrounds. We find UHECR injection models with a wide range of chemical compositions consistent with the spectrum and elongation rate measurements of Auger. An all-intermediate mass to all-heavy nuclei composition consistent with the data can lead to a considerable suppression (up to two orders of magnitude) of the cosmogenic neutrino flux in comparison to the all-proton case. However, the data is also consistent with a proton-dominated spectrum with a small admixture of heavy nuclei, in which case the cosmogenic neutrino spectrum is very similar to that predicted in the all-proton scenario. In this latter case, kilometer-scale neutrino telescopes will be expected to observe on the order of one cosmogenic neutrino event per year. In the former case, the rate will be much lower and is unlikely to be observed in current or planned experiments.

II. THE SPECTRUM AND CHEMICAL COMPOSITION OF ULTRAHIGH ENERGY COSMIC RAYS

In this section, we calculate the spectrum and chemical composition of UHECRs at Earth, for various choices of spectrum and composition as they are injected at their sources. We then compare our results to the recent measurements of the PAO to place constraints on the characteristics of the UHECRs at injection.

First we consider the simple case of an all-proton spectrum. In Fig. 1 we show the UHECR spectrum after propagation for protons injected with a spectrum of $dN/dE \propto E^{-\alpha}$, and exponentially cutoff above $E_{\max} = (10^{22}\,{\rm eV})/26$. (Throughout our study, we adopt an energy cutoff which scales with the atomic number (electric charge) of the nuclei species, $E_{\max} \propto Z$. This is motivated by the fact that, according to the Hillas criterion [17], cosmic ray sources are able to accelerate nuclei species to a maximum energy proportional to their charge. Our definition of $E_{\max}$ corresponds to the energy cutoff for iron nuclei, with $Z = 26$, and will be accordingly lower for lighter chemical species.) We have allowed the normalization of the extragalactic and galactic components of the UHECR spectrum, as well as the energy at which the galactic component is exponentially cutoff, to vary freely. In each frame, the spectrum shown is for the choices of these three parameters which lead to the best statistical fit to the spectrum measured by the PAO [6]. Here and throughout our study, we have adopted a galactic component with a spectral slope of $\alpha_{\rm Gal} = 3.6$ (below the exponential cutoff). We find that for α in the range of 2.1 to 2.4, an all-proton UHECR spectrum is consistent with the measured PAO spectrum [6] at the 95% confidence level.

An all-proton spectrum, however, appears to be inconsistent with the PAO elongation rate measurements [7]. In Fig. 2, we contrast the PAO measurements of $X_{\max}$ (right frame) to the measurements of previous UHECR cosmic ray observatories (left frame), and compare these results to the expected values for an all-proton or all-iron UHECR composition, as calculated using three different hadronic physics models (EPOS 1.6 [18], QGSJET-III [19] and SIBYLL 2.1 [20]). Regardless which of these models is used, the data appears to require the presence of a substantial fraction of heavy or intermediate mass nuclei in UHECRs. With this in mind, we now study the shape of the UHECR spectrum as predicted for heavier cosmic ray species. For details of our treatment of ultrahigh energy cosmic ray nuclei propagation, see Ref. [21]. For other studies on this topic, see Ref. [22].

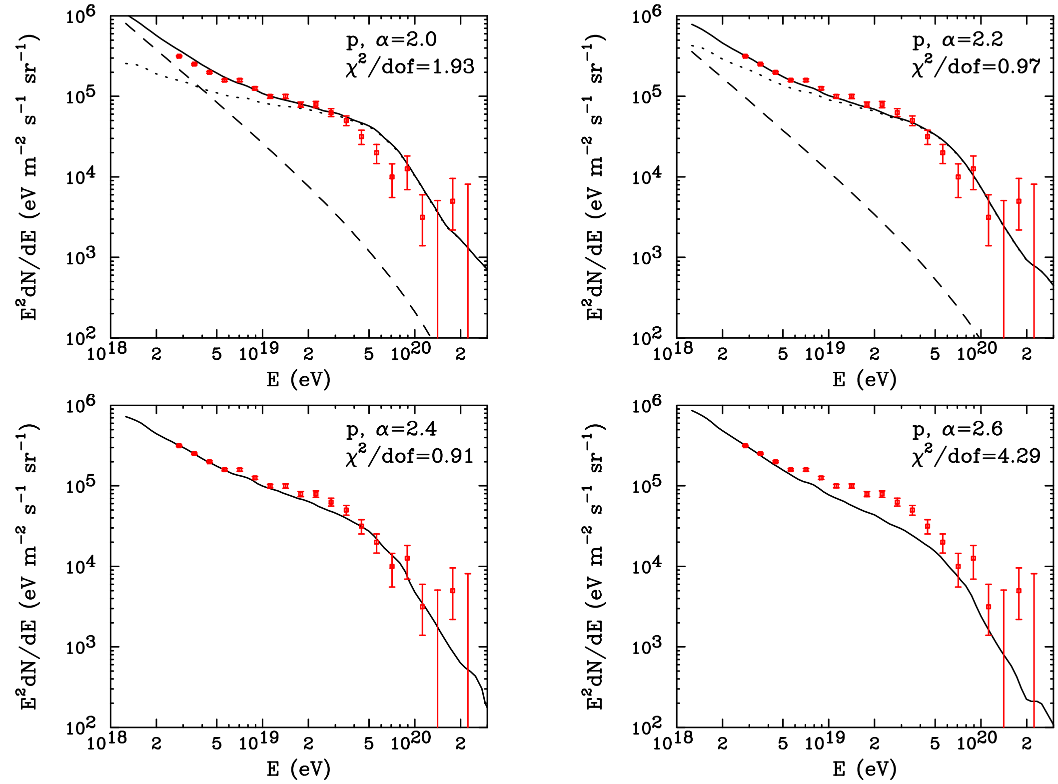

FIG. 1: The best fit spectrum for an all-proton UHECR composition for injected spectra with power-law slopes of 2.0, 2.2, 2.4 and 2.6. The dotted, dashed and solid lines denote the extragalactic, galactic and combined components, respectively. In the lower two frames, the best fit includes a negligible galactic component.

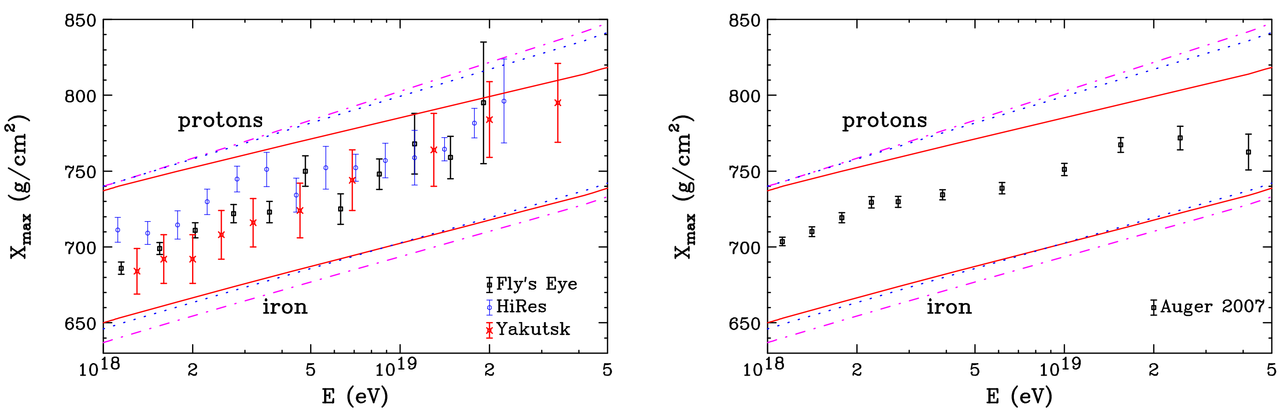

FIG. 2: The values of $X_{\rm max}$ as a function of energy as measured by Fly's Eye [23], HiRes [10] and Yakutsk [24] (left frame) and as measured by the PAO [7] (right frame). The measurements are compared to the predictions for an all-proton and all-iron UHECR composition, using three different hadronic physics models. The magenta dot-dashed, red solid and blue dotted contours correspond to the models EPOS 1.6, QGSJET-III and SIBYLL 2.1, respectively.

In Fig. 3, we show the UHECR spectrum after propagation for an injected composition consisting entirely of helium, nitrogen, silicon or iron. We show results for various values of the spectral index, α, and have taken $E_{\rm max} = (10^{22}\,{\rm eV}) \times ({\rm Z}/26)$, where Z is the electric charge of the injected species of nuclei. In each case, we find that smaller values of α are preferred than for an all-proton spectrum. In particular, a spectral slope of 1.6–2.1 is able to provide good fits, as opposed to 2.1–2.4 for protons.

We have also calculated the average composition of the UHECR spectrum for each of these nuclear species, after the effects of propagation are accounted for. In Fig. 4, we have plotted the average of the logarithm of the atomic mass of the UHECRs, as a function of energy, for various choices of injected nuclei species. The solid lines denote the

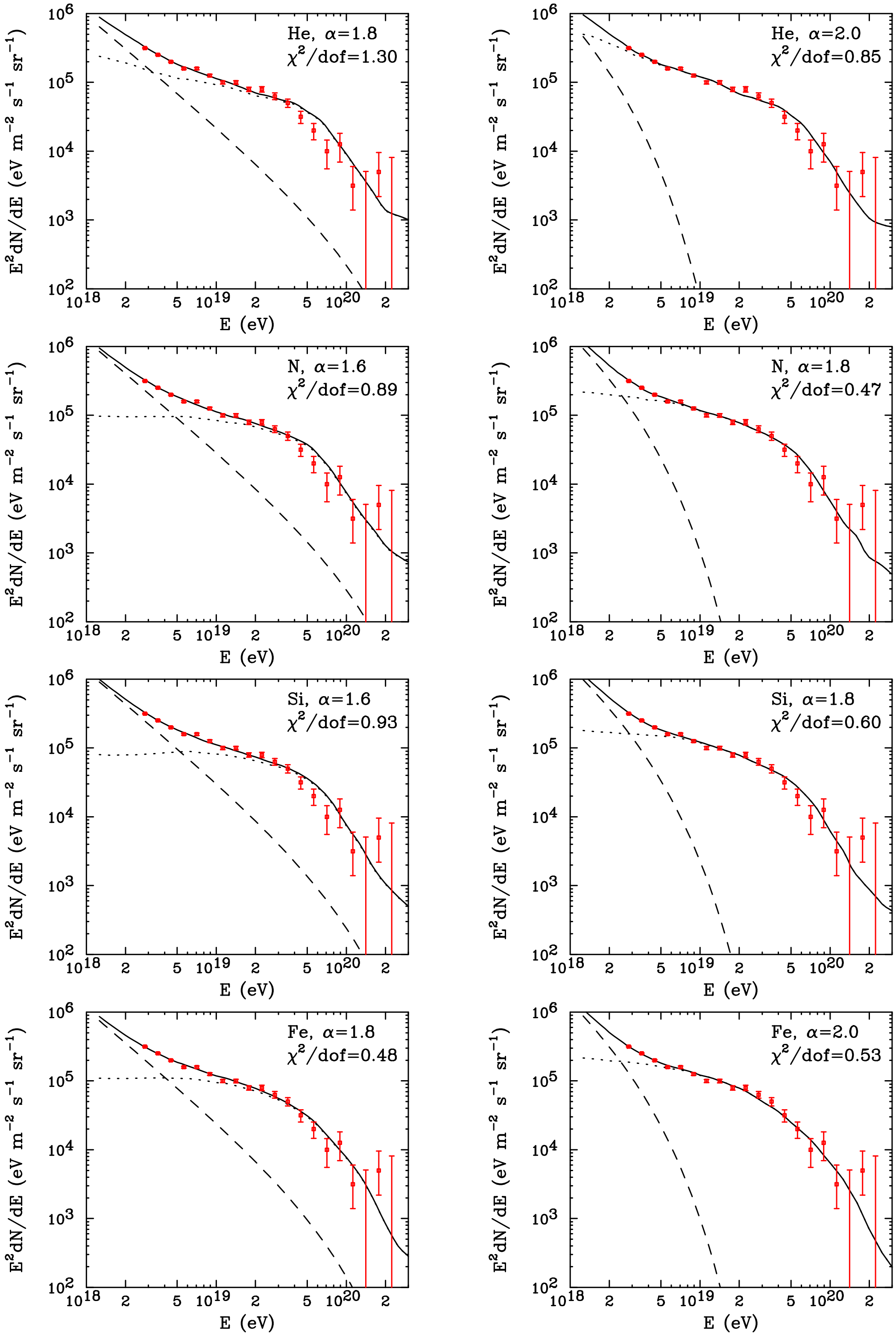

FIG. 3: The best fit spectrum for an all-helium, all-nitrogen, all-silicon or all-iron UHECR composition (at injection) for different injected power-law slopes. The dotted, dashed and solid lines denote the extragalactic, galactic and combined components, respectively.

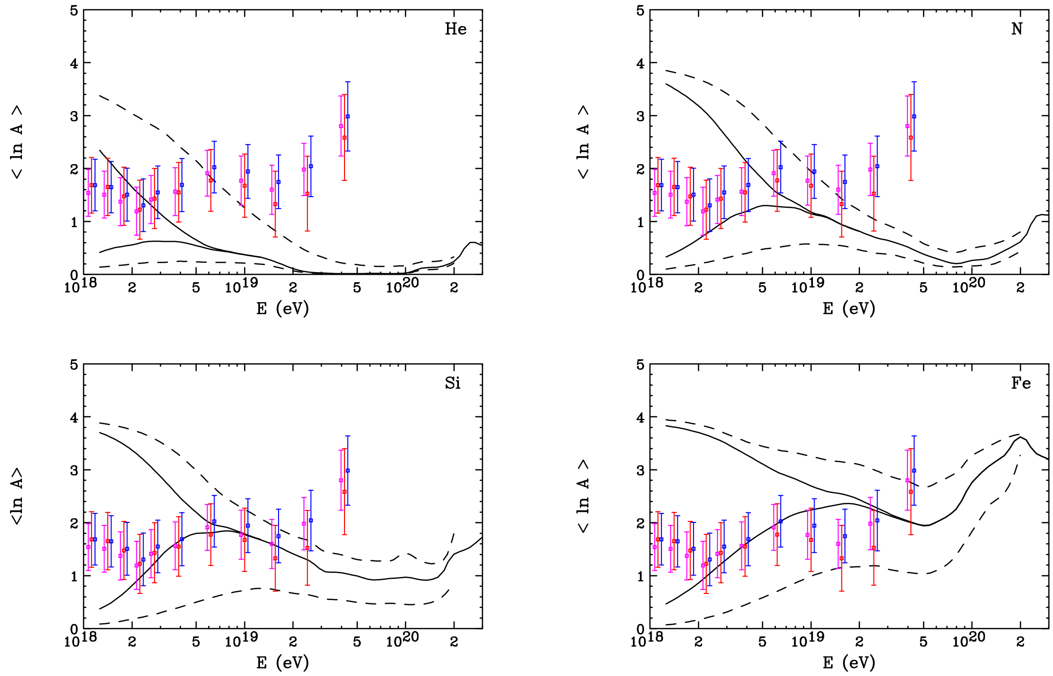

FIG. 4: The average composition at Earth for pure helium, nitrogen, silicon or iron nuclei (at injection). The solid lines denote the model best fit to the PAO spectrum, with the range shown below $\sim 10^{19}$ eV resulting from variations in the composition of the galactic component. The range denoted by the dashed lines is that which is consistent with the spectrum measured by the PAO (within the 95% confidence level). In each case, an exponential cutoff above $E_{\rm max} = 10^{22}\,{\rm eV} \times ({\rm Z}/26)$ was assumed. The error bars correspond to measurements of the elongation rate by the PAO using EPOS 1.6 (magenta, offset left), QGSJET-III (red, center) and SIBYLL 2.1 (blue, offset right), and in each case include both statistical and systematic uncertainties.

result using the parameters (spectral index and energy cutoff of the extragalactic component and energy cutoff of the galactic contribution) which provide the best fit to the PAO's spectrum measurement [6]. The dashed lines denote the range over which we find good fits to the PAO spectrum (within the 95% confidence level). We have made no assumptions regarding the galactic composition, which results in a wide range of possible average compositions below $\sim 10^{19}$ eV.

In Fig. 4, the error bars shown correspond to the PAO measurements of the elongation rate [7]. To translate between this quantity and the average of the logarithm of the composition ($< \ln A >$), a model of the hadronic physics involved must be adopted. In the figure, we show results corresponding to three hadronic models (EPOS 1.6 [18], QGSJET-III [19] and SIBYLL 2.1 [20]). The error bars shown denote both the statistical errors and systematic uncertainties.

It should be noted that the interactions of the highest energy cosmic rays occur with center-of-mass energies well above those probed at collider experiments. These models are thus based on extrapolations from lower energy accelerator data. In the future, it will become increasingly possible to distinguish between the effects of chemical composition and currently unknown hadronic physics through the detailed analysis of all observables related to composition (e.g., elongation rate, spread of $X_{\rm max}$) together with energy spectrum and anisotropy measurements. Because of the limited statistics available at these extreme energies, a definitive analysis including anisotropy measurements [8] will have to await several years of data accumulation.

So far, we have fixed the exponential cutoff in the injected spectrum of UHECRs to $E_{\rm max} = 10^{22}\,{\rm eV} \times ({\rm Z}/26)$, where Z is the atomic number of the nuclei species. If the value of $E_{\rm max}$ is lowered, we find that the injected spectrum must be further hardened to fit the spectrum measured by the PAO. For $E_{\rm max} = 10^{21}\,{\rm eV} \times ({\rm Z}/26)$, for example, we find that protons and iron require α in the range of 1.4–1.9 and 1.4–2.0, respectively. More generally, lower values of $E_{\rm max}$ require harder spectral indices. We did not consider values of α below 1.4. We found no acceptable fits for helium, nitrogen or silicon with this choice of $E_{\rm max}$. If we consider $E_{\rm max} = 10^{20}\,{\rm eV} \times {\rm Z}/26$, we find an acceptable fit only for iron, with α=1.4–1.7.

The value of the energy cutoff adopted also affects the average UHECR composition which is expected to be observed at Earth. In Fig. 5, we show the expected composition for an all-iron injected spectrum with $E_{\rm max} = 10^{21}\,{\rm eV}$ and $E_{\rm max} = 10^{20}\,{\rm eV}$. Lowering the maximum energy to which UHECRs are accelerated results in a considerably heavier composition at Earth.

Of course, the UHECR spectrum can also be generated through the injection of a mixture of protons and various

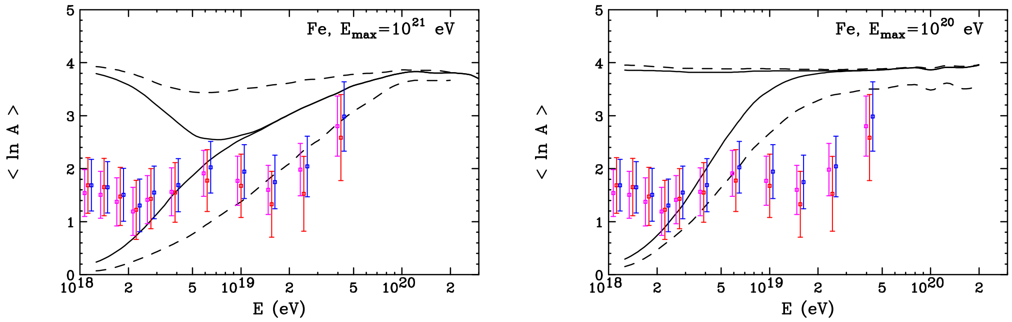

FIG. 5: The average composition at Earth for a pure iron UHECR spectrum at injection, for two values of the exponential cutoff in energy. The solid lines denote the best fit model, with the split below $\sim 10^{19}$ eV resulting from variations in the composition of the galactic component. The range denoted by the dashed lines is that which is consistent with the spectrum measured by the PAO (within the 95% confidence level). The error bars denote the $X_{\rm max}$ measurements using EPOS 1.6 (magenta, offset left), QGSJET-III (red, center) and SIBYLL 2.1 (blue, offset right).

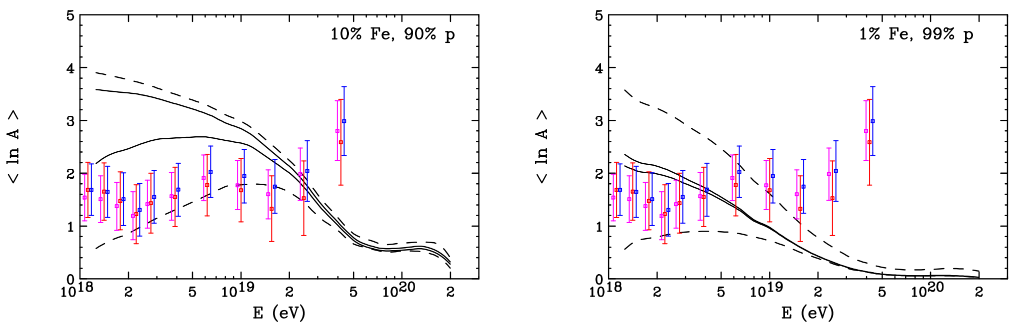

FIG. 6: The average composition at Earth for two mixtures of iron nuclei and protons in the injected spectrum. In each frame, an exponential energy cutoff of $E_{\rm max} = 10^{22}\,{\rm eV} \times ({\rm Z}/26)$ has been used. The solid lines denote the best fit model, with the split below $\sim 10^{19}$ eV resulting from variations in the composition of the galactic component. The range denoted by the dashed lines is that which is consistent with the spectrum measured by the PAO (within the 95% confidence level). The error bars denote the $X_{\rm max}$ measurements using EPOS 1.6 (magenta, offset left), QGSJET-III (red, center) and SIBYLL 2.1 (blue, offset right).

species of nuclei. In Fig. 6, we plot the average composition at Earth found for mixtures of iron nuclei and protons injected in sources of UHECRs. We find that even a very small fraction of injected iron nuclei can dominate the observed spectrum and composition at Earth, essentially because ultrahigh energy heavy nuclei, on average, travel further than protons.

After considering both the spectrum [6] and elongation rate [7] measurements made by the PAO, we find a fairly wide range of spectral indices and compositions which are consistent with the observations. In considering the composition, we consider only the 5 highest energy bins, where the extragalactic component of the UHECR spectrum is most likely to dominate. Varying the injected spectral index (α), the exponential energy cutoff ($E_{\rm max}$) and the injected chemical composition, we find the following results. An all-iron injected spectrum can fit the data well for α =1.4-2.1, depending on the choice of $E_{\rm max}$ which is adopted. All-silicon and all-nitrogen spectra can fit for α =1.6-2.0 and 1.6-1.9, respectively. An all-helium or all-proton injection spectrum is, however, not consistent with the data.

Protons with an admixture of as little as 3% (1%) iron or 7% (2%) silicon, can be consistent with all measurements for $E_{\rm max} = 10^{22}\,{\rm eV}\,(10^{21}\,{\rm eV}) \times {\rm Z}/26$. Nitrogen is consistent only if injected in equal or greater amount as protons.

III. PREDICTIONS FOR THE COSMOGENIC NEUTRINO SPECTRUM

Ultrahigh energy protons above the “GZK cutoff” [11] interact with the cosmic microwave and infrared backgrounds as they propagate over cosmological distances. These interactions generate pions and neutrons, which decay to produce neutrinos. The accumulation of these neutrinos over cosmological time is known as the cosmogenic neutrino flux.

UHECR nuclei also interact with the cosmic microwave and infrared backgrounds, undergoing photodisintegration.

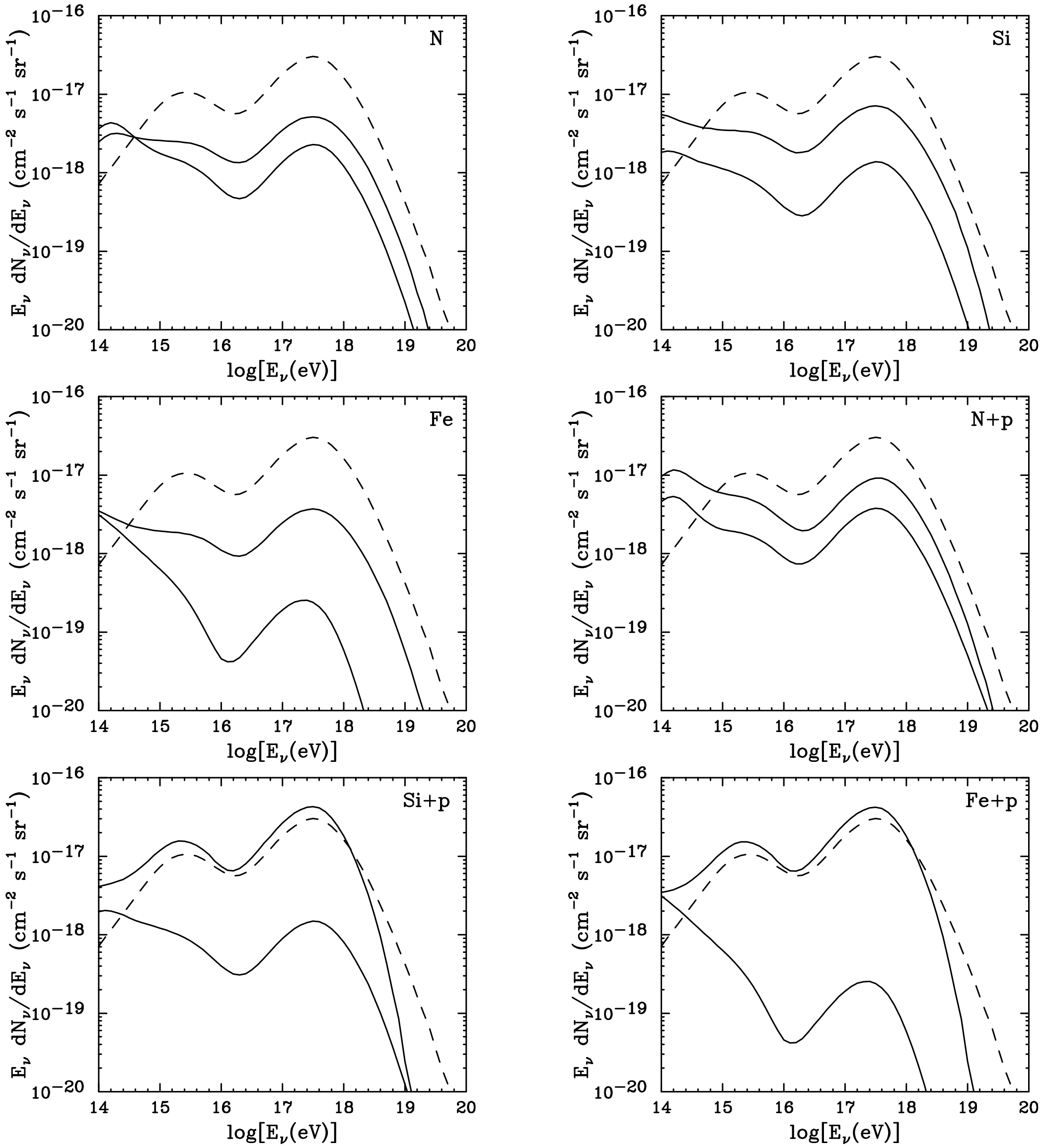

FIG. 7: The range of cosmogenic neutrino spectra we find for various chemical species which are consistent with both the PAO spectrum and $X_{\rm max}$ measurements. In each case, we have considered model parameters in the range $\alpha = 1.4 - 3.0$ and $E_{\rm max}/Z = 10^{20} - 10^{22}$ eV (although models with $E_{\rm max}/Z$ below approximately 10^{21} eV were found to be inconsistent with the data). In the N+p, Si+p and Fe+p frames, we show the results for combinations of injected nuclei and protons. In each frame, we show for comparison as a dashed curve the prediction for an all-proton spectrum with $\alpha = 2.2$ and $E_{\rm max} = 10^{22}$ eV. The solid lines denote the models with the highest and lowest rates predicted in a neutrino telescope such as IceCube.

The disassociated nucleons then interact with the cosmic microwave and infrared backgrounds to produce cosmogenic neutrinos. In the limit that the cosmic backgrounds are opaque to cosmic ray nuclei, full disintegration occurs and the resulting cosmogenic neutrino spectrum is not dramatically different from that predicted in the all-proton case (assuming the cosmic ray spectrum extends to high enough energies to produce protons above the GZK cutoff). In contrast, if a significant fraction of cosmic ray nuclei remain intact, the resulting flux of cosmogenic neutrinos can be considerably suppressed.

The predicted neutrino flux depends on the chemical composition and spectrum of the injected cosmic rays. In Fig. 7, we plot the spectrum of the cosmogenic neutrinos for various scenarios. In each frame, we show the maximal and minimal neutrino spectra (in terms of the resulting event rate in a neutrino telescope) for a wide range of spectral parameters (α, $E_{\rm max}$ and normalization) which were found to be consistent with the PAO measurements of the UHECR spectrum and elongation rate. We have considered values of these parameters in the range of $\alpha = 1.4$ to 3.0 and $E_{\rm max}/Z = 10^{20}$ to 10^{22} eV. In the first three frames, we have assumed pure nitrogen, silicon and iron at injection, respectively, and find the resulting neutrino flux to be suppressed compared to the all-proton prediction by a factor between approximately 3 and 100. The smallest cosmogenic flux is found in the case of an all-iron injected spectrum, exponentially cutoff above 10^{21} eV. In this case, the spectrum of disassociated protons is cutoff above 10^{21} eV/56 $\approx 2 \times 10^{19}$ eV, which is slightly below the GZK cutoff.

In the last three frames of Fig. 7, we consider the case of a mixed composition at injection. We find that the PAO data can be fitted if 50–100% of the injected particles are nitrogen nuclei. Mixtures of silicon and iron nuclei with protons, in contrast, are acceptable with as little as 2% and 1% heavy nuclei, respectively. In these cases the cosmogenic neutrino flux is only slightly altered from the all-proton prediction.

A number of experimental programs are underway to detect high and ultrahigh energy cosmic neutrinos (for reviews, see Ref. [25]). These efforts include large volume detectors, such as IceCube at the South Pole [13] and KM3 in the Mediterranean [26]. In Table I, we show the event rates predicted in a kilometer-scale neutrino telescope for various choices of injected spectra and chemical composition found to be consistent with the PAO spectrum and elongation rate measurements. The rates were calculated following the treatment described in Ref. [27].

Although we have not calculated the corresponding rates here, other experimental efforts to observe ultrahigh energy cosmic neutrinos include the balloon-borne radio detector ANITA [14], the under ice radio array RICE [28], and the PAO itself, which hopes to detect neutrinos as either quasi-horizontal, deeply-penetrating events, or as Earth-skimming, tau-neutrino induced events [9]. Future programs to use underwater acoustic detectors [29], radio antennas in rock salt [30], extensions of IceCube [27] and space-based cosmic ray detectors (*i.e.* JEM/EUSO) [31] are also being considered.

We have neglected in this study the effects of extragalactic magnetic fields on the propagation of UHECRs. If such particles are significantly deflected over cosmological distances, then the cosmogenic neutrino flux may be somewhat altered from the results shown here. We also note that event rates at neutrino telescopes are expected to have a significant contribution from neutrino emission from the sources themselves. The impact of heavy nuclei in the injected cosmic rays on such neutrino fluxes has been discussed elsewhere [32].

Composition	α	$E_{\rm max}/Z$	Muons (km^{-2} yr^{-1})	Showers (km^{-3} yr^{-1})
100% N	1.6-1.9	10^{22} eV	0.20-0.0081	0.15-0.0064
100% Si	1.6-2.0	10^{22} eV	0.21-0.045	0.16-0.035
100% Fe	1.6-2.1	10^{22} eV	0.11-0.014	0.085-0.012
100% Fe	1.4-1.7	10^{21} eV	0.019-0.0076	0.017-0.0075
50% N, 50% p	1.8-2.1	10^{22} eV	0.23-0.13	0.18-0.10
50% Si, 50% p	1.6-2.1	10^{22} eV	0.30-0.095	0.22-0.075
50% Si, 50% p	1.4-1.5	10^{21} eV	0.059-0.051	0.050-0.043
7% Si, 93% p	2.0-2.2	10^{22} eV	0.69-0.66	0.52-0.50
2% Si, 98% p	1.4-1.8	10^{21} eV	0.75-0.59	0.60-0.47
50% Fe, 50% p	1.6-2.1	10^{22} eV	0.15-0.043	0.11-0.034
10% Fe, 90% p	1.4-1.9	10^{21} eV	0.14-0.10	0.11-0.080
3% Fe, 97% p	2.1	10^{22} eV	0.68	0.51
1% Fe, 99% p	1.4-1.9	10^{21} eV	0.74-0.53	0.59-0.43
100% p (for comparison)	2.2	10^{22} eV	0.76	0.60

TABLE I: The rates of muon and shower events in a kilometer-scale neutrino telescope (such as IceCube or KM3) from cosmogenic neutrinos for a range of choices of injected spectra and chemical composition consistent with both the PAO spectrum and $X_{\rm max}$ measurements. For comparison, we have also shown the event rates for the case of an all-proton spectrum with $\alpha = 2.2$ and $E_{\rm max} = 10^{22}$ eV. We find models consistent with the PAO data which predict rates very similar to those found in the all-proton case, and models in which the event rates are suppressed by up to two order of magnitude.

IV. SUMMARY AND CONCLUSIONS

Utilizing as inputs the energy spectrum and composition of the ultrahigh energy cosmic rays injected from extragalactic sources, we have determined a range of models consistent with the recent PAO measurements of the cosmic ray spectrum and elongation rates. The results of our analysis may be summarized as follows:

- Consistency with the data can be achieved if the injected spectrum consists of either (*a*) entirely intermediate mass (C, N, O) or heavy (Si, Fe) nuclei, or (*b*) protons with even a very small admixture (1-10%) of heavy elements. An injected composition consisting solely of protons or light nuclei, in contrast, does not provide an acceptable fit to the elongation rate data.

- If the UHECR spectrum is dominated by intermediate mass or heavy nuclei, the resulting neutrino flux (from the photopion interactions of nucleons liberated through photodisintegration, or via neutron decay) is expected to be suppressed relative to the all-proton prediction by a factor of approximately 3 to 100, leading to event rates at IceCube within the range of approximately 0.2-0.007 muons and 0.16-0.006 showers per year. This suppression is, in part, the result of the disassociated nucleons possessing too little energy to undergo photopion interactions with CMB photons (*i.e.* they are below the "GZK cutoff"). An injected composition of protons with a very small (1-10%) admixture of heavy nuclei, however, will generate a cosmogenic neutrino flux similar to an all-proton input, while simultaneously providing a fully acceptable fit to the PAO data.

As a final comment, we note that if future observations reveal an anisotropic distribution of UHECR arrival directions (such as point sources, for example), then a significant fraction of the cosmic rays are likely to be protons rather than heavy nuclei (whose large electric charge would lead to a loss of directionality in the intervening magnetic fields). Since an injected composition consisting solely of protons is disallowed by the PAO data, the only remaining possibility would be a proton-dominated injection spectrum with a small admixture of heavy nuclei. This would imply that neutrino telescopes such as IceCube will attain discovery reach of a high energy diffuse neutrino flux within a few years of observations.

Acknowledgments

We would like to thank Tom Weiler, Francis Halzen and Teresa Montaruli for interesting comments and discussion. This work has been supported by the US Department of Energy, the National Science Foundation grant PHY-0224507, NASA grant NAG5-10842, STFC Senior Fellowship PPA/C506205/1, a MPIK Fellowship, and the EU network 'UniverseNet' (MRTN-CT-2006-035863).

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