IceCube has recently published the observation of 37 events of TeV-PeV energies. We show that the angular distribution, the spectrum and the muon to shower ratio of these events can not be explained by atmospheric neutrinos. We obtain an excellent fit, however, if cosmogenic neutrinos of ultrahigh energy experience new neutral current interactions that are very soft, with only a small fraction of energy being transferred to the target nucleon. We describe models that may provide cross sections with the precise features required to fit the data and discuss the implications of our hypothesis on future observations.

1 High energy events at IceCube

IceCube can measure large energy depositions in the ice. In particular, we will be interested in recent data that they have published in Science\(^1\) and Physical Review Letters\(^2\) where the minimum energy is set at 30 TeV. It is apparent that the only thing that can get there, 2 km under the ice, and deposit energy are muons and neutrinos. IceCube can see, for example, a neutrino coming from any direction and having a neutral current (NC) interaction or a charged current (CC) interaction with no muon in the final state. In these shower events the hadronic or electromagnetic energy is absorbed within a few meters of ice, and the direction of the primary can be distinguished with an uncertainty of 15 degrees. Since in the two analyses IceCube targets non-atmospheric neutrinos, they discard events with simultaneous activity in IceTop, as most likely these neutrinos come from mesons produced in extensive air showers. IceCube can also see CC interactions of muon neutrinos, with an initial energy deposition and then a muon track crossing the detector. They select these track events if, in addition to a subthreshold activity in Icetop, the track does not start in the detector boundary.

After cuts IceCube selects 37 events. Despite their efforts to eliminate atmospheric muons, IceCube estimate that 8.4 ± 4.2 events could still be muons entering the detector from outside,
which seems consistent with the 5 events (one of them containing two coincident muons from unrelated air showers) where the track starts near the detector boundary. We will in principle exclude these 5 downgoing events (which could be done imposing harder cuts) and assume that we are left with 32 genuine neutrino events.

To understand the data, it is essential to estimate the atmospheric $\nu$ flux and the attenuation of this flux when neutrinos propagate from the Earth surface to the detector.

Most atmospheric neutrinos come from pion and kaon decays. However, above $50 \text{ GeV}$ the spectrum of these neutrinos (in Fig. 1a) is very steep, as the parent meson tends to collide in the air and lose energy before it can decay. At energies around $10^{5.5} \text{ GeV}$ one expects that the flux becomes dominated by $\nu_\tau$ from $D$ mesons, which are less abundant in the atmosphere but shorter lived. The $\pi/K$ component has a strong dependence on the zenith angle (it is larger from horizontal directions, where these mesons find a thinner air) and is dominated by the $\nu_\mu$ flavor. The charm component is isotropic and contains $\nu_\mu$ and $\nu_\tau$ with the same frequency, together with $2\%$ of $\nu_\tau$. In Fig. 1a we also plot the cosmogenic neutrino flux, a few hundred neutrinos per km$^2$ and year that should dominate over the atmospheric flux one decade above the energies observed at IceCube. As for the attenuation of these fluxes, in Fig. 1b we plot the probability that a neutrino gets to the detector from different zenith angles. We see that at IceCube energies the absorption by the Earth is only important from $\theta_z > 110^\circ$ (i.e., more than $20^\circ$ below the horizon). In particular, a $100 \text{ TeV}$ (1 PeV) neutrino has in average a $50\%$ ($20\%$) probability to reach IceCube from $110^\circ < \theta_z < 180^\circ$. Cosmogenic neutrinos are almost completely suppressed at inclinations below the horizon.

The previous arguments motivate an analysis that includes three direction bins of similar angular size: downgoing, with declinations $-90^\circ \leq \delta < -20^\circ$ ($\delta = \theta_z - 90^\circ$), near-horizontal ($-20^\circ \leq \delta < +20^\circ$) and upgoing ($+20^\circ \leq \delta < +90^\circ$). It is important to distinguish the near-horizontal bin because it includes the largest atmospheric $\nu_\mu$ flux and also because, unlike upgoing directions, horizontal directions are not affected by attenuation. A two bin analysis (just up and downgoing events) would average and erase these crucial features in the neutrino flux, whereas a larger number of bins is not adequate to the still thin statistics.

Our simulation of the atmospheric background provides the results in the second column of Table 1.

We have included two energy bins and have distinguished between the two event topologies. An inspection of the data (summarized in the first column) reveals two clear results: (i) The
Table 1: Data, atmospheric background, excess from a $E^{-2}$ diffuse flux, and excess from eikonal collisions of cosmogenic neutrinos ($M_5 = 1.7$ TeV, $m_c = 1$ GeV) in 988 days.

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<th>Atm</th>
<th>$E^{-2}$</th>
<th>NP</th>
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</tr>
</tbody>
</table>

UPGOING
(+20° < δ < +90°)

NEAR HORIZONTAL
(−20° < δ < +20°)

DOWNGOING
(−90° < δ < −20°)


30 – 300 TeV
300 – 3000 TeV

number and distribution of tracks is well explained by atmospheric neutrinos, as IceCube see 4 tracks for an expected background of 4.3. If we added the 5 downgoing tracks excluded in our analysis together with the 8.4 ± 4.2 muon background, we would expect a total of 12.9 track events and find only 9 in the data. (ii) There is an excess of showers that is especially significant from downgoing directions. At lower energies we find 11 events for 0.6 expected, whereas in the 300–3000 TeV bin they observe 3 showers for a 0.04 background. If we include near-horizontal directions we obtain a total of 23 events for just 6.7 expected.

IceCube then proposes a fit using a diffuse flux of astrophysical neutrinos with a $E^{-2}$ spectrum (third column in Table 1). This hypothesis that has two generic implications. First, it gives around 4.5 showers per track. The data, however shows an excess of 18.6 showers (28 observed, 9.4 expected) while there is no need for extra tracks. Second, it implies a very similar number of downgoing and near-horizontal events, but we see an excess of 13.2 downgoing events and just 1.4 extra events from near-horizontal directions. Therefore, although the statistical significance of these deviations is not conclusive yet, it is apparent that other possibilities may give a better fit. In particular, we will define a new physics framework that only introduces near-horizontal and downgoing showers (in a 1:2 ratio) with no new muon tracks from any directions.

2 Very soft collisions mediated by TeV gravity

We intend to introduce new NC interactions at very high energies, so that only cosmogenic neutrinos (with $E_\nu \approx 10^9$ GeV) experience them. TeV gravity provides an ideal ground: it becomes strong at transplanckian energies ($\sqrt{s} > M_5 \approx 1$ TeV) and it reaches long distances (it is mediated by light gravitons) that imply very large cross sections. It turns out that a modification of the usual RS framework\(^6\) does the work. The model has two free parameters, $M_5$ and the 5-dim curvature $k$ (the length of the extra dimension is used to fit $M_P$). The second parameter defines the mass $m_n \approx \left(n + \frac{1}{2}\right) k\pi$ of the KK gravitons, and a value $k \leq 50$ MeV will imply large cross sections at ultrahigh energies while avoiding cosmological\(^7\) and astrophysical bounds.

We have shown\(^5\) that, at distances between $1/m_c$ and $1/M_5$, this set up gives the same gravitational potential as an ADD model\(^8\) with just one flat extra dimension.

The processes relevant at IceCube will be scatterings with large impact parameter: longer than the typical ones to form a black hole (and thus with a larger cross section) but still shorter than $l/m_c$, so that gravity is still purely 5-dimensional. In these processes\(^9,10\) the incident neutrino interacts with a parton in the target nucleon, transfers a very small fraction $y = (E_\nu - E_{\nu'})/E_\nu$ of its energy and keeps going with almost the same energy. Using the eikonal approximation the amplitude can be calculated in impact parameter space as a sum of ladder and cross-ladder diagrams. In Fig. 2 we can see that at low energies the new physics is negligible and neutrinos interact with matter only through $W$ and $Z$ exchange. Above an energy threshold
Figure 2—(a) $\nu N$ cross sections for processes mediated by TeV-gravity and by $W$ exchange. (b) Differential cross sections $y d\sigma / dy$ for $E_\nu = 10^9$ GeV. In both panels $M_s = 1.7$ TeV and $m_e = 5$ GeV (solid), 50 MeV (dashed).

$E_\nu = M_s^2/(2m_N) \approx 10^6$ GeV the gravitational cross section grows fast and becomes much larger than the standard one at $E_\nu \approx 10^8$ GeV. This large cross section, however, is very soft: the neutrino mean free path in ice becomes short ($\approx 10$ km at $10^9$ GeV) but the fraction of energy deposited in each interaction is small ($(y) \approx 10^{-5}$).

3 Fit of the IceCube events

Our model will explain the IceCube data using soft collisions of cosmogenic neutrinos. Three observations are here in order. (i) The new physics only adds neutral current interactions: new showers but no new muon tracks. (ii) At cosmogenic energies neutrinos can reach the detector only from downgoing and horizontal directions: no new upgoing events. (iii) Notice that these eikonal interactions do not stop the neutrino, it can interact in the ice several times before reaching the detector.

In the fourth column of Table 1 we give the contribution of these eikonal interactions to the different bins. The new physics introduces showers in the downgoing and near horizontal bins in a 2 to 1 ratio. After adding the atmospheric background, it provides the most accurate fit of the data. In particular, the likelihood ratio $^{11}$

$$-2 \ln \lambda = \sum_i^N 2 \left( E_i - X_i + X_i \ln \frac{X_i}{E_i} \right)$$

(1)

gives a significant difference between our hypothesis and IceCubes's:

$$-2 \ln \lambda^{NP} = 5.9, \quad -2 \ln \lambda^{E^{-2}} = 15.4 .$$

(2)

If the 5 ambiguous tracks were included in the analysis, we would obtain similar values:

$$-2 \ln \lambda^{NP} = 7.3, \quad -2 \ln \lambda^{E^{-2}} = 15.1 .$$

(3)

4 Summary and discussion

The observation by IceCube of 37 events with energy above 30 TeV is a very interesting result. The interpretation of these events in terms of an astrophysical neutrino flux with $E^{-2}$ spectrum gives an acceptable fit, but it introduces some tension with the data in the following regards:
• In the data there is no excess of muon tracks, which can be explained with atmospheric neutrinos. However, an astrophysical neutrino flux favors equipartition between the three flavors, which implies 1 track per each 4.5 extra showers.

• IceCube’s fit prefers an astrophysical flux dominated by $\nu_e$ and $\nu_\tau$. The electron flavor, however, introduces events at the Glashow resonance ($E_\nu = 6.4$ PeV) that have not been seen yet. Moreover, in their analysis the neutrino flux from charm decay (that should dominate the atmospheric flux at $10^{5.5}$ GeV) is left as a free parameter end then fitted to zero.

• IceCube’s hypothesis implies the same number of events in the downgoing and the near-horizontal bins, whereas the data shows a clear preference for the former bin.

We have proposed a different interpretation that implies a better fit: cosmogenic neutrinos, with a flux correlated with the ultrahigh energy cosmic ray flux, experience new NC interactions of very soft nature where they deposit a small fraction of energy. Our hypothesis introduces only shower events, it does not see the Glashow resonance, and it predicts a 2:1 ratio for the number of events in the downgoing and near-horizontal direction bins. We have shown that models of TeV gravity provide cross sections with the required features.

An increased statistics could then distinguish between both hypotheses. In addition, a larger detection volume in IceCube (a possibility that is currently under study) would introduce another clear difference between both scenarios. The cosmogenic neutrino flux is very low, so our interpretation requires a large cross section with matter at ultrahigh energies. As a consequence, an increased volume would necessarily imply double-bang events inside the detector, a topology that could not be explained with standard physics.

Acknowledgments

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