The GZK Bound and Strong Neutrino-Nucleon Interactions above $10^{19}$ eV: a Progress Report

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Abstract. Cosmic ray events above $10^{19}$ eV have posed a fundamental problem for more than thirty years. Recent measurements indicate that these events do not show the features predicted by the GZK bound. The events may, in addition, display angular correlations with points sources. If these observations are confirmed for point sources further than 50-100 Mpc, then strong interactions for the ultra-high energy neutrino are indicated. Recent work on extra space-time dimensions provides a context for massive spin-2 exchanges which are capable of generating cross sections in the $1 - 100$ mb range indicated by data. Some recent controversies on the applicability of extra-dimension physics are discussed.

I THE GZK PUZZLE

For more than 35 years it has been known extra-galactic proton cosmic rays should not exceed the energy of about $5 \times 10^{19}$ eV. This is the GZK bound [1]. Year after year, observations have continued to defy this result [2]. Recent observations of showers with reliably determined energies above $10^{20}$ eV [3] deepen the puzzle.

The GZK bound is as basic as the Big Bang and the Standard Model. The bound is obtained by attenuation of ultra-high energy (UHE) protons on the cosmic microwave background. The threshold of $5 \times 10^{19}$ eV is kinematic, representing a center of mass energy sufficient for production of electron-positron pairs and nuclear resonances. The cross sections for these reactions and the density of microwave background photons are known. So the attenuation of protons is known, and exponential attenuation will eliminate protons from sources more about 50 Mpc from the Earth. There are not enough sources within 50 Mpc to explain the data, making the origin of the GZK-violating events very mystifying. Speculative models such as unstable superheavy relic particles and topological defects can create particles of high enough energy, but also require sources within the same limited sphere. A
hint of correlations between observed event directions and cosmologically-distant sources [4], if confirmed, also indicates something very mysterious.

The only elementary particle that could cross the requisite intergalactic distances of about 100 Mpc or more is the neutrino. The only electrically neutral, stable particle that could explain correlations with cosmologically-distant sources is also the neutrino. Flux estimates of UHE neutrinos produced by extra-galactic sources and GZK-attenuated nucleons and nuclei vary widely, but suffice to account for the shower rates observed. The neutrino would be a natural candidate for the events, if its interaction cross section were large enough [5].

The neutrino-nucleon total cross section $\sigma_{tot}$ is the crucial issue. In the Standard Model $\sigma_{tot}$ is based on small-$x$ QCD evolution and $W^\pm, Z$ exchange physics. Cross sections of order $10^{-4} - 10^{-5}$ mb are predicted for the region of $10^{20}$ eV primary energy. This is far too small to explain the data: so perhaps new physical processes may be at work.

A The $\nu N$ Cross Section with Massive Spin-2 Exchange

Total cross sections at high energies are dominated by characteristics of the t-channel exchanges. The growth of $\sigma_{tot}$ with energy, in turn, is directly correlated with the spin of exchanged particles.

For this reason the GZK-puzzle cannot be explained by considering new spin-1 exchanges. New $W$- or $Z$-like massive vector bosons would produce $\sigma_{tot}$ growing at the same rate as the standard one, and normalized below it. Indeed any new neutrino physics must not disturb the agreement of laboratory data with 4-Fermi physics in the low energy region. At the same time the GZK-violating data indicates a cross section growing with energy that must greatly exceed the Standard Model growth by $10^{20}$ eV. How is this possible?

The paradox is beautifully resolved with massive spin-2 exchange. The fascinating possibility of massive spin-2 exchange has recently become popular in the context of hidden “extra” dimensions [6]. Kaluza-Klein (KK) excitations of the graviton are believed to act like a tower of massive spin-2 particle exchanges. We calculate the effect using the Feynman rules developed by several groups [7]. We find neutrino-nucleon cross section values at $E_\nu = 10^{20}$ eV in the $1 - 100$ mb range from mass scales in the $1 - 10$ TeV range. Interestingly, this range of masses is just that indicated by the extra-dimensions phenomenology, and this range of cross sections is just that indicated by the GZK-violating data.

What about low energies? With spin-2 exchange, $d\sigma/dt$ grows like $s^2$ and $\sigma$ like $s^3$ in the low-energy, perturbative region (with a cutoff on $t$, then one power of $s$ in the total cross section is replaced by the cutoff, of course). The new contributions to $\sigma_{tot}$ are naturally orders of magnitude below the Standard Model component in the entire regime where neutrino cross sections have been measured. Nor is any miracle needed for the neutrino interactions to emerge above ordinary cosmic ray events above $10^{19}$ eV. That is because the GZK attenuation process must set in,
uncovering a spectrum of neutrinos just at the point where protons get attenuated away. Our model of neutrinos and massive spin-2 exchange explain the GZK-violating events consistent with all known experimental limits, as shown in Fig. 1.

**B Updates and Controversies**

This is an exciting area with rapid progress on many applications.

Striking signatures appear in predictions of signals in planned $Km^3$-scale cosmic neutrino detectors. The 1 TeV to 10 PeV region will be explored, much like the existing AMANDA [8] and RICE [9] detectors. In this regime the predicted [10] ratio of upward to downward neutrino-induced showers differs substantially from the Standard Model, creating a nice diagnostic for new physics.

Horizontal air showers develop over long distances and probe smaller cross sections. Using essentially our enhanced cross section with $s^1$ behaviour, but with
different parameter choices, the authors of Ref. [11] link horizontal shower studies
to extra dimension physics. They show how fundamental scales up to 10 TeV can
be probed. Detailed studies of shower characteristics generated by our model for
various cross sections are also underway [12]. We find that the neutrino-induced
and proton-induced showers cannot be distinguished on a shower-by-shower basis.
There are exciting prospects for finding signals of new physics in shower angular
distributions.

A recent re-calculation within the same Kaluza-Klein KK framework [13] in-
cludes the “brane recoil” effects advocated by [14]. After making several technical
points, the authors of Ref. [13] present a cross section that is basically equivalent
to our $s^2$ growth model. They conclude that the resulting cross section is too small
to explain the UHE cosmic ray showers. However they do not consider all the
parameter choices allowed by current experimental limits and hence we find their
conclusions unsupported.

Acknowledgments: We thank Tom Weiler, Prashanta Das, Faheem Hussain,
and Sreerup Raychaudhuri for useful discussions. This work was supported in part
by U.S. DOE Grant number DE-FG03-98ER41079 and the Kansas Institute for
Theoretical and Computational Science.

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