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Neutrino–nucleon cross-section at ultra-high energies in models with large extra dimensions

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Abstract. We examine whether the models with large extra dimensions can provide an explanation for the GZK violating ultra-high energy cosmic rays (UHECR). In these models the neutrino–nucleon cross-section rises rapidly with energy and hence cosmic rays might be identified with neutrinos. We calculate the neutrino–nucleon cross-section at ultra high energies by assuming that it is dominated by the production of p-branes. We perform the calculation in a generalized Randall–Sundrum model and Lykken–Randall model and find cross-sections of the order of 100 mb at neutrino energies of 10^{20} eV, which is required for explaining UHECR events.

Keywords. Models beyond standard model; cosmic ray interactions.

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Low-scale gravity models [1–3] lead to the possibility that the neutrino–nucleon cross-section at ultra-high energies may be several orders of magnitude larger than what is predicted by the standard model. However at higher center of mass energies, $\sqrt{s} > M_*$, where M_* is of the order of TeV, there does not exist any reliable procedure to calculate the cross-section. In ref. [4] we estimated the cross-section, assuming that it increases as s^2, in the high-energy regime in the presence of factorizable large extra dimensions and found that neutrino–nucleon cross-sections are of the order of one to several hundred mb with the precise value dependent on the model used and on the choice of M_*. Such large values of the neutrino–nucleon cross-section are very interesting since then the neutrino becomes a candidate for explaining UHECR events. In all the extra dimension models calculated neutrino–nucleon cross-section values are not large enough to solve the UHECR mystery but they put stringent constraints on these models. It has been proposed that at large s, the scattering cross-section in these models is dominated by black hole or brane production. It is found that the neutrino–nucleon cross-section for black hole production is of the order of 0.1 mb at $s \approx 10^{12}$ GeV^2 which is insufficient to explain UHECR showers. But it could generate horizontal showers which are not seen in detectors till now.

In ref. [5] it is proposed that cross-section for brane production is large compared to that of black hole production cross-section in the presence of n factorizable asymmetric extra dimensions out of which m dimensions are compactified on length scale of order $L \leq M_*^{-1}$ and remaining $n - m$ dimensions are compactified on length scale of order $L' \gg M_*^{-1}$.

In this paper we calculate the neutrino–nucleon total cross-section for p-brane production $\sigma_{\nu p}$ at ultra-high energies within the framework of a generalized RS model [3] and the model proposed by Lykken and Randall in [6]. We modified the RS1 model by adding m small factorizable extra dimensions compactified on a m-torus. The model consists of two 3-branes with opposite tension situated at orbifold points along the warped direction in $(4 + m + 1)$-dimensional space-time. Then we find solution to the Einstein equations for the above set-up for the certain choice of bulk and brane energy–momentum tensor and analyze the kk spectrum in the low energy limit [7].

From the analysis of the kk spectrum we find that in the low energy limit the theory reduces to RS1 model except that the size of the warped extra dimension is taken to be of order 1 fm. The fundamental mass scale is 1 TeV. In this limit the masses of the kk-modes are quantized in mass scale of the order of GeV instead of TeV scale as in RS1 model. Since there are a large number of modes present, we can ignore the few low-lying modes and the sum over the remaining modes can be done by changing the summation to an integration as in the ADD case [1].

We generalize the Lykken and Randall [6] in exact analogy with the above construction. We can now construct p-brane solutions in these models such that the brane is completely wrapped around the m extra compact dimensions.

The parton level brane production cross-section $\hat{\sigma}_{\text{brane}}$ for p-brane of mass $M_p = \sqrt{\hat{s}}$ is given by

$$\hat{\sigma}_{\text{brane}}(\hat{s}) = \pi r_p^2, \tag{1}$$

where r_p is the radius of the p-brane and is given by eq. (8) of ref. [5]. The brane production processes are expected to give dominant contributions when $s \gg M_*^2$.

The total cross-section can be computed using

$$\sigma(\nu N \to \text{brane}) = \sum_i \int_{x_{\min}}^{1} \mathrm{d}x \hat{\sigma}_{\text{brane},i}(xs) f_i(x, Q) \ , \tag{2}$$

where f_i is the parton distribution function corresponding to the ith parton, $x_{\min} = M_*^2/s$ and Q is the typical momentum scale of the collision which is taken to be the brane mass. We use the CTEQ parton distributions for our calculation. Since the parton distributions are not known beyond $Q = 10$ TeV, we set Q equal to this value if the brane mass exceeds 10 TeV. The minimum value of x is obtained by assuming that branes are produced with masses M_p greater than M_*.

It is clear from figures 1a and 1b that there exists a large range of parameter space where the neutrino–nucleon cross-section is of the order of 100 mb or above for the primary neutrino energy of 10^{11} GeV in case of one large extra dimension and six small extra dimensions. This is the cross-section values required in order that neutrino can be a primary for producing UHECR showers in the upper atmosphere. In contrast to the assumed t-channel graviton exchange in ref. [4], here the neutrino delivers its entire energy in a single collision. Hence, in the present case the position of the shower maximum may be indistinguishable from a hadron

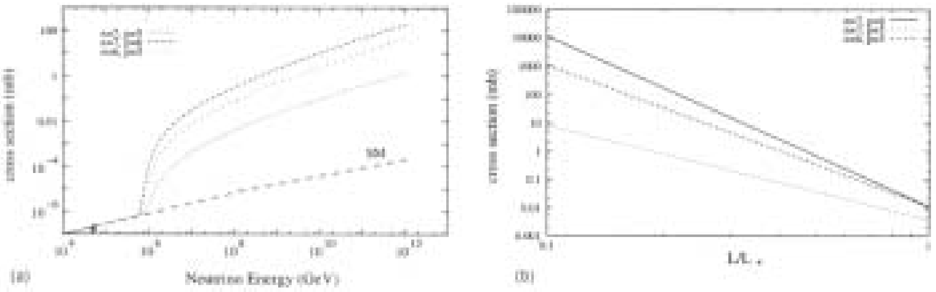

Figure 1. In figure 1a we plot the neutrino–nucleon cross-section for different values of p and n and with $L/L_* = 0.25$. The scale of quantum gravity is taken to be 1 TeV. The highest energy HERA data point and the cross-section obtained in standard model (SM) are also shown for comparison. The dependence of total cross-section on L/L_* is shown in figure 1b for some representative choice of parameters, p and n and with the neutrino energy fixed to 10^{11} GeV.

primary of equivalent energy. We also point out that our cross-section does not violate any constraints imposed by unitarity. Furthermore the models and parameter ranges considered in this paper are not ruled out by the low energy data [7].

After formation the p-brane will decay. In analogy with black hole evaporation, we expect that branes will decay into gravitons and matter fields. The emitted gravitons will not be detected. Hence only a fraction of the particles that are produced will be responsible for generating the shower and the primary energy may be significantly underestimated. This implies that for a shower of energy E we need a primary neutrino of energy E' which is somewhat larger than E. The precise amount of energy which goes into gravitons is model-dependent.

In conclusion we have shown that in low-scale gravity models the neutrino–nucleon cross-section is of the order of or larger than 100 mb for a large range of parameter space allowed by current experimental constraints. This makes the neutrino a candidate for explaining the cosmic ray events which appear to violate the GZK bound. Future cosmic ray observatories will be able to confirm or rule out this hypothesis.

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