Effects of Electroweak Instantons
In High-Energy Neutrino Telescopes

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Abstract
We demonstrate that next generation high-energy neutrino telescopes may reveal the existence of interactions induced by standard model electroweak instantons. The energy spectrum, the angular distribution, and the quark and lepton multiplicity of events in the detector each provide signatures which can indicate the presence of these interactions. High-energy neutrino telescopes may be capable of searching for signals at energies far beyond the reach of the next generation colliders.
I. INTRODUCTION

Instantons are classical solutions of non-Abelian gauge theories in Euclidean space-time \cite{1}, that represent tunneling transitions between topologically inequivalent vacua. The processes induced by electroweak instantons could be extremely interesting since they violate baryon+lepton number ($B+L$) conservation \cite{2}. The transition rate for the tunneling processes are exponentially suppressed at low energies compared to the energy barrier separating the vacua, referred as the “sphaleron” energy ($E_{sph} \approx \pi M_W/\alpha_w \sim 8 \text{ TeV}$) \cite{3}. However, at high temperatures \cite{4}, or high energies \cite{5}, the transition rate may be unsuppressed. It has thus been of great interest to explore the impact of the sphalerons on generating the baryon number asymmetry of the Universe \cite{6}, and to ask if these effects can be observed in high-energy reactions such as at future colliders \cite{3, 7}.

It is a challenge from a theoretical point of view to reliably estimate the two-body scattering rate for the instanton-induced processes near and above $E_{sph}$ \cite{8}. In view of the close analogy of QCD, parton scattering amplitudes induced by electroweak instantons have been calculated using a perturbation method in the instanton background, with the saddle-point approximation \cite{9}. It was argued that, due to the very large pre-exponential factor in the cross section formula \cite{10}

$$\sigma_0 \approx \left(\frac{2\pi/\alpha_w}{M^2_W}\right)^{7/2} \approx 5.3 \times 10^3 \text{ mb}, \quad (1)$$

the scattering cross section may be sufficiently enhanced at parton center-of-mass energies of about $E \geq 4\pi M_W/\alpha_w \sim 30 \text{ TeV}$, leading to possibly observable effects at a Very Large Hadron Collider (VLHC) and at future ultra-high energy cosmic ray experiments \cite{11}. Recently, a new calculation based on a generalized semi-classical approach has been performed to determine the exponent function \cite{12}. Their numerical results demonstrated a severe exponential suppression, extended to energies as high as $30 \times E_{sph} \sim 250 \text{ TeV}$, under the simplification of the $S$-wave dominance. Beside the phenomenological and observational excitement motivating searches for electroweak instanton effects, it would be of significant importance to obtain a quantitative description of such interactions and to test the different theoretical approaches, such as the two mentioned above. An initial comparison has just been made \cite{10} as we were completing this work.

We are approaching the era of neutrino astrophysics in which it will become possible to observe neutrinos of extra-galactic origin, at energies of PeV to EeV scales. Present experiment, such as AMANDA \cite{13}, Baikal \cite{14} and RICE \cite{15} have successfully measured the atmospheric neutrino spectrum to energies up to $\sim 10 \text{ TeV}$ and have placed limits on any diffuse high-energy neutrino flux beyond this energy. IceCube \cite{16}, with a cubic kilometer effective volume, will be sensitive to charged and neutral current neutrino interactions from $\sim \text{ TeV}$ to the highest observed energies. Furthermore, planned experiments such as ANITA \cite{17} and EUSO/OWL \cite{18} will have even greater sensitivities to ultra-high energy neutrinos. For a review of high-energy neutrino astronomy, see Ref. \cite{19}.

In this Letter, we study in detail the instanton or sphaleron-induced processes in high-energy neutrino telescopes, following some early proposals \cite{20}. Neutrino telescopes can measure neutrino scattering cross sections at energies far greater than those accessible to colliders. At energies around $E_\nu \sim 100 \text{ TeV}$, the Earth becomes opaque to neutrinos with the standard model (SM) cross sections. Taking advantage of this feature, comparing the flux of neutrinos observed traveling through the Earth (up-going events) to the flux from above the detector
FIG. 1: Neutrino-nucleon cross sections via standard model electroweak instanton-induced processes. The dotted line represents the calculation of Ringwald. The dashed line represents the calculation of Bezrukov et al., using a pre-factor given in Eq. (1). The solid line is the standard model neutral+charged current prediction. Also shown as horizontal dashed lines are the cross sections which correspond to interaction lengths equal to the vertical down-going and horizontal depths of IceCube.

(down-going), the neutrino-nucleon cross section can be inferred [21]. More generally, the zenith angle distribution of events in an underground detector can, given a sufficient flux, reveal this cross section. Satellite-based experiments and air shower arrays cannot perform this task as effectively, as they are not designed to observe neutrino events over as great an angular distribution, or at as great a range of energies. A large volume, underground detector is ideal for this task. For this reason, we focus on the IceCube detector, which is presently under construction and will be completed well before other post-LHC collider projects can be realized.

In our analysis, we consider both of the calculations for the cross section of instanton-induced neutrino-nucleon interactions described earlier. For the calculation by Ringwald, we perform the numerical evaluation by closely following the formalism in Ref. [9]. As for the calculation by Bezrukov et al. (BLRRT), only the exponential function is given [12]. We have thus assumed a constant pre-factor for the cross section given by Eq. (1), multiplied by the exponential function parameterized from [12]. We note that this may have been a very crude estimate for the cross section since the full pre-factor as in [9] is energy-dependent and it may decrease at higher energies.

The cross sections predicted by these calculations are shown in Fig. 1 by the dotted and dashed curves for the Ringwald’s and BLRRT calculations, respectively. As expected, the cross section grows sharply above the threshold, with a $\nu N$ center-of-mass energy about 30 TeV for the Ringwald’s calculation, and as high as about 250 TeV for the BLRRT calculation. For comparison, the standard model neutrino-nucleon total cross section of neutral and charged
FIG. 2: Energy distribution of showers generated in neutrino-nucleon interactions via standard model electroweak instanton-induced processes, with two assumed neutrino fluxes. The dotted line represents the calculation of Ringwald. The dashed line represents the calculation of Bezrukov et al., using a pre-factor given in Eq. (1). The solid line is the standard model neutral+charged current prediction. Currents is also shown (solid line), where the three active flavors of neutrinos have been included and the CTEQ-5 parton distribution functions are used. Also illustrated as horizontal dashed lines are the cross sections which correspond to interaction lengths equal to the vertical down-going and horizontal depths of IceCube (D Depth and H Depth). It is in the range between these lines that distinctive features in the angular distribution of down-going events appear. For a neutrino flux $\Phi$, the number of events $N_{\nu}$ observed as hadronic or electromagnetic showers in a neutrino detector of effective volume, $V$, is given by the convolution over energy of the quantity $V \times \Phi \times n \times \sigma_{\nu}$. Here $n$ is the density of the target that interacts with a neutrino with cross section $\sigma_{\nu}$ to produce a shower.

In Fig. 2, the energy spectrum of down-going shower events predicted in the IceCube experiment is shown. In the Ringwald’s calculation (dotted line), as the center-of-mass neutrino-nucleon energy exceeds the sphaleron energy threshold near 30 TeV, the number of events increases dramatically above the standard model prediction. Even farther above this energy, however, more of the neutrinos are absorbed in the ice before reaching the detector and the event rate is suppressed. This drastic “bump” structure in the spectrum indicates the sharply enhanced cross section at the sphaleron energy threshold position. The peak of this bump occurs at the associated neutrino energy and is mainly generated by charged current electron neutrino interactions. The “shoulder” slightly to the left of the bump is from neutral and charged current interactions which generate showers less energetic than the incident neutrino. These features occur at considerably higher energies for cross sections found using the calculation by Bezrukov et al. In this approach, due to the exponential suppression of instanton-induced interactions well above the sphaleron energy, observations of these interactions will be considerably more difficult to study in neutrino telescopes, or colliders.
The left frame of Fig. 2 considers a flux of neutrinos equal to the upper bound found by Waxman and Bahcall \[24\]. This choice of flux represents neutrinos from compact engines, such as gamma ray bursts or hadronic blazars. The limit of Waxman and Bahcall is somewhat controversial and it has been argued that larger high-energy neutrino fluxes may be possible from such sources \[25\]. The right frame considers the neutrino flux from the interactions of ultra-high energy protons with the cosmic microwave background, called the cosmogenic neutrino flux \[26\]. We have used the cosmogenic flux as calculated in Ref. \[27\]. The cosmogenic neutrino flux can be reliably calculated from the observed flux of ultra-high energy protons. Therefore, the choice of this flux is quite conservative. It is interesting to note that at EeV energies, the Waxman-Bahcall bound is not far above the conservative cosmogenic prediction. For this reason, in our discussion the detected neutrino flux plays a secondary role.

Figure 3 shows the zenith angle distribution of showers above 1 EeV in a kilometer-scale detector. Up-going events correspond to \(-1 < \cos\theta_{\text{zenith}} < 0\), whereas down-going events correspond to \(0 < \cos\theta_{\text{zenith}} < 1\). For standard model interactions, the distribution (solid curve) is nearly flat for down-going events, and essentially no up-going events occur due to very efficient neutrino absorption by the Earth at these energies. For models with larger cross sections from instanton-induced interactions, vertical down-going events become more frequent, producing more events near \(\cos\theta_{\text{zenith}} \sim 1\). At zenith angles near the horizon, \(\cos\theta_{\text{zenith}} \sim 0\), more of the neutrinos are absorbed and the rate can be suppressed. We have chosen the shower threshold of 1 EeV to optimize the angular effects for the case of Ringwald’s calculation.

Another interesting characteristic feature of instanton-induced processes is the large multiplicity of final state particles and the violation of \(B + L\). The basic operators involving quark and lepton fields are of the form \(\langle qqq\ell^n g \rangle\), where \(n_g = 3\) is the number of fermion generations. It has been argued that the processes involving multiple gauge bosons and Higgs bosons, like \(\langle qqq\ell^n W^m H^m \rangle\), can be significantly enhanced \[5\]. A typical neutrino-induced event could thus be

\[
\nu_e u \rightarrow d\bar{d} + \bar{c}c\bar{s}\mu^+ + \bar{t}t\bar{b}\tau^+ + nW + mH. \tag{2}
\]

With both quarks and leptons of all three generations involved simultaneously at the primary production, this type of events should look quite unique. It is, however, difficult to predict how the events would exactly look like in the IceCube detector given the fact that the particles are highly collimated and will be challenging to separate.

Shown in Table I are the event rates predicted in a kilometer-scale high-energy neutrino telescope, such as IceCube. Rates are shown for the standard model charged plus neutral current (CC+NC), as well as for the calculations by Ringwald and by BLRRT (including CC+NC). Rates are shown for three (shower) energy ranges, chosen to illustrate the features in the energy spectrum associated with each approach (see Fig. 2). For the Ringwald’s calculation, the event rate predicted for the cosmogenic neutrino flux is about 0.7 per year in the narrow range of 0.4 to 2 EeV, a factor of ten above the SM (CC+NC) prediction. This rate is somewhat higher (1.2) for the flux given by the Waxman-Bahcall bound. Either of these cases provide a possible signature for observations over several years. The predictions of BLRRT are considerably more difficult to test, however. In the peaked region of the energy spectrum, at 10 to 20 EeV, only on the order of 0.03 events per year are expected. Although this is much larger than the SM (CC+NC) prediction, it will be very challenging for kilometer-scale instruments to observe this signature. An order of magnitude larger detector in effective volume would be needed to probe such a scenario.

It has been proposed that ultra-high energy neutrinos undergoing instanton-induced inter-
actions may have generated many of the observed cosmic ray events above the GZK cutoff [11]. Although it would be extremely interesting to establish this interpretation, it will be difficult to determine with confidence that this is the case with air shower experiments. Neutrinos with mb scale cross sections have similar experimental signatures to protons and, therefore, will be difficult to distinguish.

Future satellite-based cosmic ray experiments, such as EUSO/OWL [18], may be able to observe similar numbers of ultra-high energy neutrino events compared to IceCube [28]. Much like ground based cosmic ray experiments, EUSO/OWL does not have the phenomenological advantages of a deeply buried neutrino telescope described in this paper. Such experiments will have a more difficult time identifying neutrino-nucleon cross section enhancements.

In summary, the SM electroweak instantons may provide observable signatures in kilometer-scale high-energy neutrino telescopes. The large deviations of the neutrino-nucleon cross section from the charged and neutral current prediction found in these calculations provide distinctive features in both the spectrum and angular distribution of events in the detector. These variations reflect both the increased probability of a neutrino interacting in the detector and the increased probability of being absorbed in the Earth. Another qualitative feature would be presented by the particle content of the events (all three generations of quarks and leptons with $B + L$ violation).

The calculation of Ringwald’s should be unambiguously tested by IceCube before post-LHC
### TABLE I: Event rates (showers) in a high-energy neutrino telescope per year, per cubic kilometer of effective volume. Rates are shown for the standard model charged plus neutral current (CC+NC), as well as for the calculations by Ringwald and by BLRRT (including CC+NC). Rates for three (shower) energy ranges are shown. These were selected to illustrate the features in the energy spectrum associated with each approach.

| Energy Range       | CC+NC | Ringwald | BLRRT |
|--------------------|-------|----------|-------|
| 0.4 EeV and above  | 0.24  | 1.3      | 0.26  |
| 0.4 – 2.0 EeV      | 0.15  | 1.2      | 0.15  |
| 10 – 20 EeV        | 0.013 | 0.0063   | 0.034 |

The prediction of BLRRT will be considerably more difficult to probe due to the suppression of the rate in the relevant energy region.

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