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Supersymmetric sphaleron configurations as the origin of the perplexing ANITA events

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ABSTRACT

The ANITA experiment has observed two air shower events with energy ∼ 500 PeV emerging from the Earth with exit angles of ∼ 30°. We explain ANITA events as arising from neutrino-induced supersymmetric sphaleron transitions. These high-multiplicity configurations could contain a large number of long-lived supersymmetric fermions, which can traverse the Earth and decay in the atmosphere to initiate upward-pointing air showers at large angles above the horizon. We comment on the sensitivity of new generation LHC detectors, designed to searching for displaced decays of beyond standard model long-lived particles, to test our model.

The $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ standard model (SM) of electroweak and strong interactions has recently endured intensive scrutiny at the Large Hadron Collider (LHC) using a dataset corresponding to an integrated luminosity of 63.9 fb^{-1} of 2018 pp collisions at center-of-mass energy $\sqrt{s} = 13$ TeV, and it has proven once again to be a remarkable structure that is consistent with all experimental results by tuning more or less 19 free parameters. However, the Antarctic Impulsive Transient Antenna (ANITA) experiment, designed to observe ultrahigh-energy cosmic rays and neutrinos from outer space, has detected particles that seemed to be blasting up from Earth instead of zooming down from space, challenging SM explanations [1,2]. As a matter of fact, several beyond standard SM physics models have been proposed to accommodate ANITA observations [3–10], but a convincing explanation is yet to see the light of day. In this Letter, we entertain the possibility that ANITA events originate in a supersymmetric sphaleron transition produced in the scattering of extremely high-energy ($E_\nu \gtrsim 10^{10.5}$ GeV) cosmic neutrinos with nucleons inside the Earth. Such a non-perturbative process yield a high-multiplicity final state containing several long-lived supersymmetric fermions, one of which would survive propagation through the Earth crust before decaying into SM particles to initiate an upward-pointing shower in the atmosphere, just below the ANITA balloon.

The advantages of our interpretation of ANITA events over previous supersymmetry (SUSY) models [8,9] go in two directions:

- The ratio $\mathrm{BR}(\nu N \to \mathrm{SUSY})$ of the neutrino–nucleon cross section into SUSY particles over the total νN cross section dominates over the branching ratio of charged current (CC) νN interactions. Furthermore, the particle content of the final state in sphaleron-induced transitions could contain a large multiplicity of SUSY fermions. All of this is in sharp contrast with the production of SUSY pairs in perturbation theory, for which $\mathrm{BR}(\nu N \to \mathrm{SUSY}) \lesssim 10^{-4}$ [11–15].
- The νN scattering process requires a center-of-mass energy $\sqrt{s} \gtrsim 245$ TeV, thus probing $E_\nu \gtrsim 10^{10.5}$ GeV. In this energy range a large flux of neutrinos is expected from the decay of cosmic strings [16]. Moreover, in our model all three neutrino flavors would contribute to the ANITA signal.

We begin our discussion by highlighting the main characteristics of ANITA events and after that we provide a phenomenological analysis of data.

After three balloon flights, the ANITA experiment has detected two perplexing upgoing showers with energies of (600 ± 400) PeV [1] and (560^{+300}_{-200}) PeV [2].[1] The energy estimates are

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[1] The trigger algorithm used for the second flight was not sensitive to this type of events [1].

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made under the assumption that the showers are initiated close to the event's projected position on the ice. These estimates are lowered significantly if the showers are initiated far above the ice. For example, the energy of the second event is lowered by 30% if the shower is initiated four kilometers above the ice [2]. Note that even with the 30% energy reduction, the center-of-mass energy of the collisions initiating these showers is beyond $\sqrt{s}$ of the LHC beam.

In principle, ANITA events could originate in the atmospheric decay of an upgoing τ-lepton produced through a CC interaction of a ν_τ inside the Earth [17]. However, the relatively steep arrival angles of these events (27.4° and 34.5° above the horizon) create a tension with the SM neutrino–nucleon interaction cross section. More concretely, the second event implies a propagating chord distance through the Earth $= 2R_\oplus \cos\theta_n \sim 7.2 \times 10^3$ km, which corresponds to 1.9×10^4 km water equivalent (w.e.) and a total of 18 SM interaction lengths at $E_\nu \sim 10^3$ PeV [18]. Here, $R_\oplus$ is the radius of the Earth and θ_n the nadir angle of the event. The first event emerged at $\theta_n \simeq 62.6°$ implying a chord through the Earth of 5.9×10^3 km, which corresponds to 1.5×10^4 kmw.e. for Earth's density profile [1]. Because the energy deposited in a shower is roughly 80% of the incident neutrino energy, the cosmic neutrino energy range of interest is $200 \lesssim E_\nu/\text{PeV} \lesssim 1000$. Taking the view that the event distribution is maximized at $\theta_n = 60°$, in our calculations we will consider an average chord distance in traversing the Earth of $\sim 6 \times 10^3$ km.

Next, in line with our stated plan, we study the structural properties of our model. In the mid-seventies 't Hooft pointed out that the SM does not strictly conserve baryon and lepton number [19,20]. Rather, non-trivial fluctuations in $SU(2)$ gauge fields generate an energy barrier interpolating between topologically distinct vacua. An index theorem describing the fermion level crossings in the presence of these fluctuations reveals that neither baryon nor lepton number is conserved during the transition, but only the combination $B - L$. Inclusion of the Higgs field in the calculation modifies the original instanton configuration [21]. An important aspect of this modification (called the "sphaleron") is that it provides an explicit energy scale $E_{\text{sph}} \sim M_W/\alpha_W \sim 9$ TeV for the height of the barrier, where M_W is the mass of the charged vector bosons $W^\pm$ and $\alpha_W \simeq 1/30$. When the energy reach is much lower than E_{sph} the tunneling rate through the barrier is exponentially suppressed $\Gamma_{\text{tunneling}} \propto e^{-4\pi/\alpha_W} \sim e^{-164}$. However, the sphaleron barrier can be overcome through thermal transitions at high temperatures, providing an important input to any calculation of cosmological baryogenesis [22–24]. Indeed, the rate over the barrier (thermal excitation) contains a Boltzmann factor $\Gamma_{\text{thermal}} \propto T^4 e^{-E_{\text{sph}}/T}$, and hence the rate becomes large as the temperature approaches M_W.

More speculatively, it has been suggested that the topological transition could take place in two particle collisions at very high energy [25–27]. The anomalous electroweak contribution to the partonic process can be written as

$$\hat{\sigma}_i(\hat{s}) = 5.3 \times 10^3 \; e^{-(4\pi/\alpha_W)\; F_W(\epsilon)} \;\text{mb}\,, \qquad (1)$$

where the tunneling suppression exponent $F_W(\epsilon)$ is usually referred to as the "holy-grail function" and $\epsilon \equiv \sqrt{\hat{s}}/(4\pi M_W/\alpha_W) \simeq \sqrt{\hat{s}}/30$ TeV [28–30]. Altogether, it is possible that at or above the sphaleron energy the cross section could be of $\mathcal{O}(\text{mb})$ [31].

The argument for strong damping of the anomalous cross section for $\sqrt{\hat{s}} \gtrsim 30$ TeV was convincingly demonstrated in [32,33], in the case that the classical field providing the saddle point interpolation between initial and final scattering states is dominated by spherically symmetric configurations. This $O(3)$ symmetry allows the non-vacuum boundary conditions to be fully included in extremizing the effective action. In [34] it was shown that a *sufficient* condition for the $O(3)$ dominance is that the interpolating field takes the form of a chain of "lumps" which are well-separated, so that each lump lies well into the exponentially damped region of its nearest neighbors. However, we are not aware of any reason that such lumped interpolating fields should dominate the effective action. It is thus of interest to explore the other extreme, in which non-spherically symmetric contributions dominate the effective action (and let experiment rather than theory [35–37] be the arbiter). Thus far, the searches for instanton-induced processes in LHC data have shown no evidence for excesses of high-multiplicity final states above the predicted background [38–40].

Of particular interest here would be an enhancement of the νN cross section over the perturbative SM estimates, say by an order of magnitude, for $E_\nu \gtrsim 10^{10.5}$ GeV. To get an estimate of this cross section we first note that for the simple sphaleron configuration s-wave unitarity is violated for $\sqrt{\hat{s}} > 4\pi M_W/\alpha_W \sim 36$ TeV [31]. If for $\sqrt{\hat{s}} > 36$ TeV we saturate unitarity in each partial wave, then this yields a geometric parton cross section πR^2, where R is some average size of the classical configuration. As a fiducial value we take the core size of the Manton–Klinkhamer sphaleron, $R \sim 10^{-2}$ fm. In this simplistic model, the νN cross section is found to be

$$\sigma_{\nu N}^{\text{black disk}}(E_\nu) = \pi R^2 \int_{x_{\min}}^{1} \sum_{\text{partons}} f(x)\, dx\,, \qquad (2)$$

where $x_{\min} = \hat{s}_{\min}/s = (36)^2/2m_N E_\nu \simeq 0.065$, where m_N is the mass of an isoscalar nucleon, $N \equiv (n+p)/2$, in the renormalization group-improved parton model. In the region $0.065 < x < 3\,(0.065)$ the parton distribution function for the up and down quarks is well approximated by $f \simeq 0.5/x$, so the expression for the cross section becomes

$$\sigma_{\nu N}^{\text{black disk}}(E_\nu) \simeq \pi R^2 \;(0.5)\;(\ln 3)\;(2/2) \simeq 1.5 \times 10^{-30}\;\text{cm}^2\,, \qquad (3)$$

where the last factor of 2/2 takes into account the (mostly) 2 contributing quarks (u, d) in this range of x, and the condition that only the left-handed ones contribute to the scattering. This is about 80 times the SM cross section. Of course this calculation is very approximate and the cross section can easily be smaller by a factor of 10 (e.g., if R is 1/3 of the fiducial value used). The sphaleron production cross section derived "professionally" [41] is consistent with our back-of-the-envelope estimate, and shows an enhancement of the νN cross section over the perturbative SM estimates by about an order of magnitude in the energy range $E_\nu \gtrsim 10^{10.5}$ GeV. Previous estimates pointed to even larger cross section enhancements above perturbative SM prediction [42,43]. In our calculations we will adopt the estimate of [41].

A point worth noting at this juncture is that the energy for the height of the barrier in SUSY models is also about 10 TeV [44], and consequently the expected production rate of supersymmetric sphaleron configurations is comparable to the SM one [45]. Most importantly, the decay BR increases if the final state contains a large number of SUSY fermions [45]. To develop our program in the simplest way, we will work within a construct with gauge mediated SUSY breaking, in which the gravitino $\psi_{3/2}$ is the lightest supersymmetric particle (LSP) and the next-to-lightest supersymmetric (NLSP) is a long-lived bino $\tilde{B}$ [46]. Note that for $M_{\tilde{B}} \sim 700$ GeV [47], NLSPs could be copiously produced through instanton-induced processes at $\sqrt{\hat{s}} \gtrsim 50$ TeV (see Fig. 3 in [45]), and could propagate inside the Earth without suffering catastrophic energy losses from electromagnetic interactions. The bino

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decays into a gravitino and a gauge boson (i.e., photon or Z-boson) with Planck-suppressed partial widths,

$$\Gamma(\tilde{B} \to \psi_{3/2}\gamma) = \frac{\cos^2\theta_{\rm W}}{48\pi M_{\rm Pl}^2}\frac{M_{\tilde{B}}^5}{m_{3/2}^2}(1-x_{3/2}^2)^3(1+3x_{3/2}^2), \qquad (4)$$

$$\begin{aligned}\Gamma(\tilde{B} \to \psi_{3/2}Z) &= \frac{\sin^2\theta_{\rm W}\beta_{\tilde{B}\to\psi_{3/2}Z}}{48\pi M_{\rm Pl}^2}\frac{M_{\tilde{B}}^5}{m_{3/2}^2}\Big[(1-x_{3/2}^2)^2(1+3x_{3/2}^2) - x_Z^2 \\ &\quad \times\Big\{3+x_{3/2}^3(-12+x_{3/2})+x_Z^4-x_Z^2(3-x_{3/2}^2)\Big\}\Big], \qquad (5)\end{aligned}$$

where $M_{\rm Pl} \sim 10^{19}$ GeV, $\sin^2\theta_W \approx 0.23$, $x_{3/2} \equiv m_{3/2}/M_{\tilde{B}}$, and $x_Z \equiv M_Z/M_{\tilde{B}}$, and where

$$\beta_{\tilde{B}\to\psi_{3/2}Z} \equiv \Big[1-2(x_{3/2}^2+x_Z^2)+(x_{3/2}^2-x_Z^2)^2\Big]^{1/2}, \qquad (6)$$

for $M_{\tilde{B}} > m_{3/2}+M_Z$, and $\beta_{\tilde{B}\to\psi_{3/2}Z}=0$ otherwise [48]. For $M_{\tilde{B}} > m_{3/2}+M_Z$, the total decay width is well approximated by

$$\tau_{\tilde{B}}^{-1} \simeq \Gamma(\tilde{B}\to\psi_{3/2}\gamma)+\Gamma(\tilde{B}\to\psi_{3/2}Z), \qquad (7)$$

and the NLSP lifetime is estimated to be

$$\tau_{\tilde{B}} \sim 5\times 10^{14}\,\frac{m_{3/2}^2}{M_{\tilde{B}}^5}\ {\rm s}, \qquad (8)$$

when masses are given in GeV [49].

Before proceeding, we pause to discuss existing limits from searches of long-lived neutral particles at the Tevatron and at the LHC. The CDF Collaboration searched for long-lived particles which decay to Z-bosons by looking for $Z \to e^+e^-$ decays with displaced vertices and excluded proper decay lengths $c\tau < 20$ cm for masses < 110 GeV [50]. Searches by D0 Collaboration exclude long-lived neutral particles of comparable lifetimes and masses [51,52]. The CMS Collaboration has searched for long-lived neutralinos decaying into a photon and an invisible particle, excluding $c\tau < 50$ cm for masses < 220 GeV [53]. The ATLAS Collaboration searched for high-mass long-lived particles that decay within the inner detector to give displaced dilepton vertices excluding $c\tau < 100$ cm [54]. ATLAS has also searched for very low mass (< 10 GeV) long-lived particles by considering pairs of highly collimated leptons [55], with sensitivity to $c\tau \lesssim 20$ cm. The most restrictive constraints on the lifetime of a long-lived particle come from a search by the ATLAS Collaboration for final states with displaced dimuon vertices in collisions at $\sqrt{s} = 13$ TeV [56]. Proper decay lengths $c\tau < 14$ m are excluded for SUSY models in which the lightest neutralino is the NLSP, with a relatively long lifetime due to its weak coupling to the LSP-gravitino. The lifetime limits are determined for very light gravitino mass and a neutralino mass of 700 GeV. Altogether, we can remain consistent with LHC bounds requiring $\tau_{\tilde{B}} \sim 44$ ns for $M_{\tilde{B}} \sim 700$ GeV. Substituting the bino lifetime in (8) we obtain $m_{3/2} \sim 122$ keV.

SUSY models with a gravitino LSP are also constrained by a variety of cosmological observations. Of relevance to our analysis: *(i)* if $\tau_{\tilde{B}} \sim 44$ ns, NLSP decay does not perturb light element abundances which are synthesized during Big Bang nucleosynthesis [57,58]; *(ii)* if $m_{3/2} \sim 122$ keV, the relic density of gravitinos can be accommodated to match observations with choice of parameters [59,60].

It takes a proper time of order $4.5 M_W^{-1}$ until the sphaleron radiation shows free-field behavior [61]. For neutrino-induced sphaleron transitions, this radiation will be emitted in a cone with half-opening angle $\delta\phi \sim \mathcal{O}(1/\gamma)$, where γ is the Lorentz factor. Taking fiducial values $E_\nu \sim 10^{10.5}$ GeV and $\sqrt{\hat{s}} \sim 50$ TeV, one can have an order of magnitude estimate $\gamma \sim 6\times 10^5$. All in all, the bino decay length in the lab frame is $\gamma c\tau \sim 8\times 10^3$ km. This means that for emerging angles $\theta_n \sim 60°$, a long-lived bino could survive the trip through the Earth. Note also that the boosted bino would have an energy $E_{\tilde{B}} \sim 420$ PeV, and after decay roughly half of its energy will be deposited in the air shower. These order of magnitude estimates are in good agreement with the energy and opening angle distributions shown in Fig. 4 of [41].

Given an isotropic $\nu+\bar{\nu}$ flux, the number of binos that emerge from the Earth is proportional to an "effective solid angle" $\Omega_{\rm eff} \equiv \int d\theta_n d\phi \cos\theta_n P(\theta_n,\phi,X)$, where $P(\theta_n,\phi;X)$ is the probability for a neutrino with incident nadir angle θ_n and azimuthal angle ϕ to emerge as a detectable $\tilde{B}$ [62,63]. $P(\theta,\phi,X)$ is a rather complicated function of various unkown (model dependent) parameters X. However, we can provide a rough estimate of the event rates if we adopt the exposure calculations of [8], which suggest a total ANITA exposure for sub-EeV emergent cosmic rays of 2.7 km^2 sr yr, for the two flights together. It is noteworthy that this exposure is orders of magnitude larger than the exposure for τ-neutrinos reported by the ANITA Collaboration [64]. This is because τ-neutrinos which do not arrive at very large nadir angles are mostly blocked by the Earth. Observation of 2 events at ANITA would require an integrated neutrino flux $\Phi_\nu(E_\nu > 10^{10.5}~{\rm GeV}) \sim 10^{-17.7}~({\rm cm}^2\,{\rm s}\,{\rm sr})^{-1}$. Interestingly, at $E_\nu \sim 10^{10.5}$ GeV, the ANITA experiment sets the most restrictive upper limit on the energy weighted cosmic neutrino flux; namely, $E_\nu\Phi_\nu(E_\nu) \lesssim 10^{-17.5}~({\rm cm}^2\,{\rm s}\,{\rm sr})^{-1}$ at 90% CL [65,66]. Note that neutrino-induced sphaleron transitions with non-negligible (missing) energy carried away by long-lived SUSY fermions would relax limits on the neutrino flux at extreme energies. We end with two comments on the neutrino flux. On the one hand, the required flux level to accommodate ANITA events may be exceptionally high by astronomical standards [67]. On the other hand, for some model parameters, such a flux of extremely high-energy ($E_\nu \gtrsim 10^{10.5}$ GeV) neutrinos is consistent with predictions from decay of cosmic strings [16]. The decay of cosmic strings also produces extremely high-energy photons and electrons that interact with the cosmic microwave background and extra galactic background light, producing an electromagnetic cascade, whose energy density is constrained by measurements of the diffuse γ-ray background [68]. A point worth noting at this juncture is that the fluxes of γ-rays and neutrinos expected from the decay of cosmic strings are consistent with existing observations [69]. Moreover, experiments are being designed to search for the neutrino signals of cosmic strings; e.g., the Lunar Orbital Radio Detector (LORD) that will fly aboard the Luna-Resurs Orbiter space mission [70].

In summary, we have provided an interpretation of ANITA events in terms of neutrino-induced supersymmetric sphaleron transitions. These high-multiplicity $B+L$ violating transitions may contain a large number of long-lived SUSY fermions, which can traverse the Earth and decay in the atmosphere to initiate an upward-pointing shower just below the ANITA balloon. As a proof of concept, we have framed our discussion in the context of a gauge-mediated breaking scheme, but this model spans only a small region of the SUSY parameter space that can accommodate ANITA events. Indeed, our interpretation of these perplexing events can be encapsulated in the product of three factors:

- the differential flux of incident neutrinos,
- the ratio of the νN cross section into SUSY particles over the total νN cross section,
- the lifetime of the SUSY fermion.

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Note these three factors are actually generic to a broad class of models in which the messenger of ANITA events does not live inside the Earth neither originate at cosmological distances. New generation LHC experiments dedicated to searching for long-lived particles (such as the ForwArd Search ExpeRiment (FASER) [71,72], the MAssive Timing Hodoscope for Ultra Stable neutraL pArticles (MATHUSLA) [73,74], and the Compact Detector for Exotics at LHCb (CODEX-b) [75]) will provide an important test both of the last two factors and of the ideas discussed in this Letter. In addition, the first factor will be tested by the future Probe Of Extreme Multi-Messenger Astrophysics (POEMMA) [76] and the Giant Radio Array for Neutrino Detection (GRAND) [77], which may directly observe neutrino-induced sphaleron transitions raining down on the Earth atmosphere.

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