Neutrino Telescopes as a Direct Probe of Supersymmetry Breaking

Ivone F. M. Albuquerque,[1] Gustavo Burdman,[2,3] and Z. Chacko[2,3]
[1]Department of Astronomy and Space Sciences Laboratory, University of California, Berkeley, California 94720, USA
[2]Theory Group, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
[3]Department of Physics, University of California, Berkeley, California 94720, USA

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We consider models where the scale of supersymmetry breaking lies between 5×10^6 and 5×10^8 GeV. In this class of theories, which includes models of mediated supersymmetry breaking, the lightest supersymmetric particle is the gravitino, and the next to lightest is typically a long-lived charged slepton with a lifetime between a microsecond and a second, depending on its mass. We investigate the production of these particles by the diffuse flux of high energy neutrinos colliding with nucleons in the Earth, and the potential for their observation in large ice or water Cerenkov detectors. The small production cross section is partially compensated by the very long range of sleptons. The signal, two well-separated parallel tracks, has very little background. Using the Waxman-Bahcall limit for the neutrino flux results in up to four events a year in km^3 experiments.

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Introduction.—The origin of the radiative stability of the weak scale is one of the most important questions in particle physics today. A natural answer requires new physics at the TeV scale. Among the candidate theories, weak scale supersymmetry remains the most attractive scenario. Although this is in no small measure due to its theoretical appeal (it is a simple and natural extension of the usual space-time symmetries), it is also favored by data from electroweak observables. These point to a weakly coupled Higgs sector, one without significant deviations from the standard model (SM) in regard to electroweak precision observables. However, supersymmetry (SUSY) must be broken since the superpartners have not yet been observed. The supersymmetric spectrum is determined by the supersymmetry breaking mechanism.

Supersymmetric models typically have a symmetry, called R parity, which ensures that the lightest supersymmetric particle (LSP) is stable. Which of the supersymmetric particles is the LSP? This is determined by the scale of supersymmetry breaking, which we denote by $\sqrt{F}$, and which can lie anywhere between 10^3 and 10^{12} GeV. If supersymmetry is broken at high scales such that $\sqrt{F}$ is larger than 10^{10} GeV, the LSP is typically the neutralino. If however supersymmetry is broken at lower scales, $\sqrt{F} < 10^{10}$ GeV, the LSP is typically the gravitino. In many models where the LSP is the gravitino, the next to lightest supersymmetric particle (NLSP) is a charged slepton, typically the right-handed stau, the supersymmetric partner of the tau lepton. Since the NLSP decays to gravitinos through interactions that are suppressed by powers of $\sqrt{F}$, if the supersymmetry breaking scale is high its lifetime can be quite large. In these scenarios we have

$$c\tau = \left(\frac{\sqrt{F}}{10^7\ \text{GeV}}\right)^4 \left(\frac{100\ \text{GeV}}{m_{\tilde{\tau}_R}}\right)^5 10\ \text{km}, \qquad (1)$$

where $m_{\tilde{\tau}_R}$ is the stau mass. Thus, for $\sqrt{F} \geq 10^7$ GeV, if these NLSPs were to be produced by very high energy collisions they could travel very long distances before decaying. In the last several years many interesting and realistic scenarios have been proposed in which the scale of supersymmetry breaking $\sqrt{F}$ is low and could lie between 5×10^6 and about 5×10^8 GeV. These include models of gauge mediation [1], gauge and Yukawa mediation [2], warped higher dimensional models in which supersymmetry is broken on an infrared brane and therefore the scale $\sqrt{F}$ has been warped down [3], theory space realizations of higher dimensional models [4], and models of supersoft supersymmetry breaking which are characterized by Dirac gauginos [5]. In all of these classes of models the NLSP is typically a right-handed stau.

The existence of diffuse fluxes of high energy neutrinos, possibly associated with the production of cosmic rays, has been widely discussed in the literature. Collisions of these high energy neutrinos with nucleons in the Earth at energies above threshold for supersymmetric production frequently result in the production of a pair of supersymmetric particles, which promptly decay into NLSPs. These typically have a high boost $\gamma_{\text{NLSP}} \simeq 1000$ or larger and therefore will not decay inside the Earth provided the supersymmetry breaking scale $\sqrt{F} > 10^7$ GeV. For $5 \times 10^6 < \sqrt{F} < 10^7$ GeV, a significant fraction of the decays will occur inside the Earth. Since the NLSP is charged, its upward going tracks could in principle be detected in large ice or water Cerenkov detectors, such as IceCube [6] or expanded versions of

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ANTARES [7] and NESTOR [8]. This is in analogy with the standard model charged current interaction giving muons, the primary signal in neutrino telescopes.

Naively, one would expect that the event rates for NLSPs (which typically have masses in the 100 GeV range) are negligible when compared to those for muons, since their production cross section must be considerably smaller than that of the SM interactions. The reason is that the SM interactions come primarily from very small values of x, the parton momentum fraction, whereas the supersymmetric process is limited to $x > m^2/2M_P E_\nu$, with m given essentially by the sum of the produced supersymmetric particles. This naive expectation is, however, misleading. The crucial observation is that the range of a slepton is much larger than that of a muon, since energy loss due to radiation sets in at much higher energies. In neutrino telescopes, muon events must be produced either right outside the detector or in it, since the muon range for the energies of interest is in the few to tens of kilometers. Thus, most of the upgoing charged current (CC) events produced in the Earth are lost. On the other hand, the range of NLSPs is typically in the hundreds to thousands of kilometers. Then, unlike for the muon [9], a significant fraction of the NLSPs produced will range into the detector.

In what follows we compute the number of NLSP events. For this purpose we calculate the SUSY production cross sections and the NLSP range.

The SUSY cross section.—In the scenarios under consideration, every νN interaction producing supersymmetric particles will result in a pair of NLSPs, which have a very long lifetime. In what follows, we will assume this lifetime to be large enough so that NLSPs do not decay in the Earth. For simplicity, we also neglect mixing with Higgsinos in the gaugino sector. The dominant process is analogous to the SM CC interactions and corresponds to the t-channel exchange of charginos producing $\nu N \to \tilde{\ell}\,\tilde{q}$, as shown in Figs. 1(a) and 1(b). The neutrino, always produced left handed by the weak interactions, can interact either with a left-handed down-type quark [Fig. 1(a)], or with a right-handed up-type quark [Fig. 1(b)]. This results in the partonic cross sections:

$$\frac{d\sigma^{(\mathrm{a})}}{dt} = \frac{\pi\alpha}{2\sin^4\theta_W}\frac{M_{\tilde{w}}^2}{s(t - M_{\tilde{w}}^2)^2}, \tag{2}$$

$$\frac{d\sigma^{(\mathrm{b})}}{dt} = \frac{\pi\alpha}{2\sin^4\theta_W}\frac{(tu - m_{\tilde{\ell}_L}^2 m_{\tilde{q}}^2)}{s^2(t - M_{\tilde{w}}^2)^2}, \tag{3}$$

where s, t, and u are the usual Mandelstam variables and $M_{\tilde{w}}$, $m_{\tilde{\ell}_L}$, and $m_{\tilde{q}}$ are the chargino, the left-handed slepton, and the squark masses, respectively. The left-handed slepton and the squark decay promptly to the lighter "right-handed" slepton plus nonsupersymmetric particles. We also include the subdominant neutralino exchange [Figs. 1(c) and 1(d)]. We take $m_{\tilde{w}} = 250$ GeV, $m_{\tilde{\ell}_L} = 250$ GeV, and three values for the squark masses, $m_{\tilde{q}} = 300$, 600, and 900 GeV. These are very representative values in the scenarios under consideration. Typically, the $\tilde{\tau}_R$ is the NLSP, being heavier only than the ultralight and the very weakly coupled gravitino. Charginos and neutralinos tend to be heavier since they also feel the $SU(2)_L$ interactions. Finally, squarks are heavier still since their masses are affected by the strong interactions. In Fig. 2 we plot the cross sections for supersymmetric production in νN interactions as a function of the neutrino energy. Also plotted for comparison is the SM charged current cross section. As advertised earlier, the

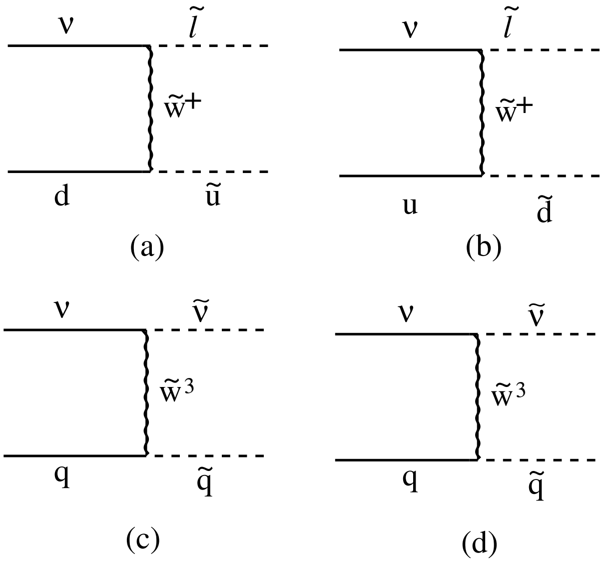

FIG. 1. Feynman diagrams for supersymmetric particle production in νN collisions. Charged current (chargino) interactions: (a) left-left interaction requiring the insertion of the gaugino mass in the t-channel line; (b) left-right interaction. Neutral currents: (c),(d). There are analogous diagrams for antineutrinos as well as for strange and charm initial quarks.

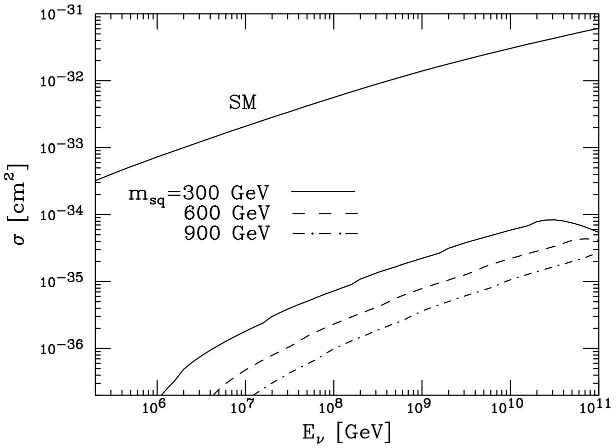

FIG. 2. νN cross sections vs the energy of the incident neutrino. The curves correspond to $m_{\tilde{\ell}_L} = 250$ GeV, $m_{\tilde{w}} = 250$ GeV; and for squark masses $m_{\tilde{q}} = 300$ GeV (solid line), 600 GeV (dashed line) and 900 GeV (dot-dashed line). The top curve corresponds to the SM charged current interactions.

SUSY cross sections are still suppressed with respect to the SM, even when well above threshold.

The NLSP range.—Once produced by the νN interactions in the Earth, the NLSP pair should range into the detector, just as the muons produced by CC events [9]. Charged particles lose energy due to ionization processes as well as through radiation. The average energy loss is given by [10]

$$-\frac{dE}{dx} = a(\beta\gamma) + c(\beta\gamma)\beta\gamma. \tag{4}$$

Here a and c characterize the ionization and radiation losses, respectively, and are slowly varying functions of the energy. The ionization loss can be approximated by

$$a(\beta\gamma) \simeq 0.08 \frac{\text{MeV cm}^2}{\text{g}}(17 + 2\ln\beta\gamma), \tag{5}$$

and is rather independent of the particle mass. On the other hand, assuming $c(\beta\gamma) \simeq$ const, the radiative energy loss can be written as $c\beta\gamma = (b_m)E$. Thus $b_\mu m_\mu = b_{\tilde\tau_R} m_{\tilde\tau_R}$, and the radiative energy loss for the NLSPs scales approximately as $1/m$ [11]. This results in a much larger range for the NLSP as compared to the muon. Current bounds on $m_{\tilde\tau_R}$ are just above 100 GeV. As a reference value we take $m_{\tilde\tau_R} = 150$ GeV. Therefore, NLSPs produced hundreds and even thousands of kilometers away are within range of the detector. This is to be contrasted with the fact that muons must be produced at distances not larger than tens of kilometers from the detector in order to be observed. As we will see, this will somewhat compensate for the suppression of the SUSY cross sections observed earlier.

Signals in neutrino telescopes.—In order to compute the event rates in neutrino telescopes, we need to know the incoming neutrino flux. The presence of cosmic neutrinos is expected on the basis of the existence of high energy cosmic rays. Several estimates of the neutrino flux are available in the literature. In most cases, it is expected that km^3 neutrino telescopes will measure this flux. Here, in order to present projections for the number of observed SUSY events, we make use of the Waxman-Bahcall (WB) limit [13] as an estimate of the cosmic neutrino flux. We consider an initial flux containing both ν_μ and ν_e (in a 2:1 ratio). Since the initial interactions (see Fig. 1) produce $\tilde\ell_L$ and these are nearly degenerate in flavor, the flavor of the initial neutrino does not affect our results. For the same reason, the possibility of large mixing in the neutrino flux is also innocuous here, with the exception of a small additional supersymmetric production in $\bar\nu_e$ scattering off atomic electrons [12]. In order to correctly take into account the propagation of neutrinos and the NLSP $\tilde\ell_R$ through the Earth, we make use of a model of the Earth density profile as detailed in Ref. [14].

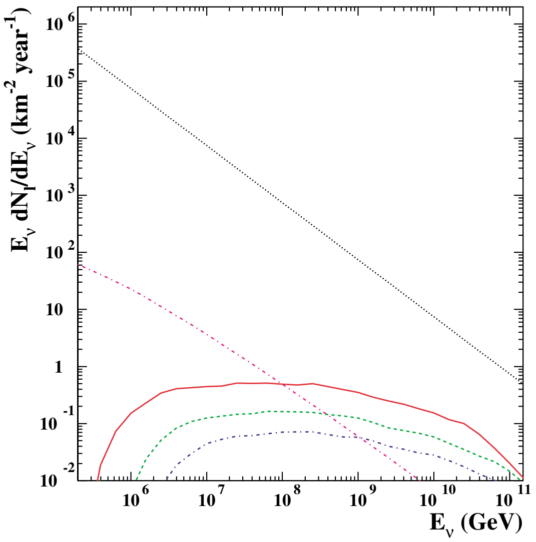

FIG. 3 (color online). Energy distribution of $\tilde\tau_R$ pair events per km^2, per year. From top to bottom: $m_{\tilde q} = 300$, 600, and 900 GeV. Here, $m_{\tilde\tau_R} = 150$ GeV and $m_{\tilde w} = 250$ GeV. Also shown are the neutrino flux at Earth and the μ flux through the detector. In all cases we make use of the WB limit for the neutrino flux.

In Fig. 3 we show the energy distribution for the NLSP pair events for three choices of squark masses: 300, 600, and 900 GeV. Also shown are the neutrino flux at the Earth in the WB limit, as well as the energy distribution of upgoing μ's. We see that, even for the heavier squarks, it is possible to obtain observable event rates. In Table I we show the event rates for $\tilde\ell_R$ pair production per year and per km^2. The rates are given for the WB flux as well as for the Mannheim-Protheroe-Rachen (MPR) flux [15], both for optically thin sources. For comparison, we also show the rates of upgoing muons. Thus, km^3 Cerenkov detectors such as IceCube, appear to be sensitive to most of the parameter space of interest in scenarios with a relatively long-lived NLSP.

Since the NLSPs are produced in pairs very far from the detector and with a very large boost, typical signal events consist of two tracks separated by $\delta R \simeq L\theta$, with L the distance to the production point ($\simeq$100–1000 km) and $\theta \simeq p^{\rm CM}_{\rm SUSY}/p_{\rm boost} \simeq 10^{-3}$–$10^{-4}$. If we consider L to be of the order of the NLSP range, then in the linear regime $\delta R \simeq$ const $\simeq 100$ m. As we have seen in the discussion following Eq. (5), for very high energies the range grows

TABLE I. Number of events per km^2 per year assuming the WB and MPR limits. The first column refers to upgoing muons. The last three columns correspond to upgoing NLSP pair events, for three different choices of squark masses: 300, 600, and 900 GeV. The number of muon events are given for energies above threshold for production of a 250 GeV $\tilde\ell_L$ plus a 300 GeV squark, i.e., 1.6×10^5 GeV.

	μ	$m_{\tilde q} = 300$ GeV	600 GeV	900 GeV
WB	106	4	1	0.5
MPR	1085	10	3	1

TABLE II. Number of events for extended IceCube [16] per year assuming ν flux is given by the WB limit. The $\tilde{\ell}_L$ and squark masses and the number of muons are as in Table I.

	μ	$m_{\tilde{q}} = 300$ GeV	600 GeV	900 GeV
1 ring, 300 m	110	5	2	1
1 ring, 1000 m	110	6	2	1
4 rings, 300 m	131	9	3	1
4 rings, 1000 m	140	16	5	2

logarithmically with energy, leading to somewhat smaller values of $\delta R \simeq (20\text{–}40)$ m. The track separation is then mildly sensitive to the stau injection energy [12]. Then, most NLSP events would consist of two parallel but well-separated tracks, and are therefore expected to be very distinctive and different from backgrounds. The most important remaining background comes from dimuon production (e.g., where the second muon comes from the production and subsequent decay of charm) and is studied in detail in Ref. [12].

Conclusions.—We have shown for the first time that neutrino telescopes are potentially sensitive to the relatively long-lived charged NLSPs which are present in a wide variety of models of supersymmetry breaking. The event rates shown in Table I are already encouraging for experimental facilities that are being built, such as IceCube. The region of the supersymmetry breaking parameter space that is available to neutrino telescopes is determined, on the one hand, by the twin requirements that the NLSP lifetime be long enough to give a signal ($\sqrt{F} \gtrsim 5 \times 10^6$ GeV), but not be so long as to disturb big bang nucleosynthesis ($\sqrt{F} \lesssim 5 \times 10^8$ GeV). Thus the observation of NLSP events at neutrino telescopes will constitute a direct probe of the scale of supersymmetry breaking. On the other hand, at the Large Hadron Collider, for most of this range of $\sqrt{F}$ the NLSP decays outside the detector and is seen through its ionization tracks, which would not constrain the NLSP lifetime significantly. Thus, we see that neutrino telescopes can be complementary to collider searches. Future upgrades of large neutrino telescopes will result in even better sensitivity. As an example, in Table II we show rates for an expanded version of IceCube [16]. In the present Letter we focused on supersymmetry. However, many other theories give rise to relatively long-lived charged particles which can be observed by neutrino telescopes [12].

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