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We investigate whether transition radiation from a particle shower crossing the interface between Earth and air and induced by an Earth-skimming neutrino can explain the upward event announced recently by the ANITA Collaboration. While the properties of the observed signal can in principle be explained with transition radiation, a conservative upper limit on the experiment's aperture for this kind of signal shows that the flux necessary for a successful explanation is in tension with the current best limits from the Pierre Auger Observatory, the IceCube neutrino detector and the ANITA balloon. We also show that in this scenario, the direction of the incoming neutrino is determined precisely to within a few degrees, combining the polarization properties of the observed events with the Earth opacity to ultra high energy neutrinos.

I. INTRODUCTION

Ultra high energy cosmic rays (UHE CR) have been detected with energies above 10^{20} eV [1, 2]. They can interact with photons of the cosmic microwave background, what limits the distance to which we can in principle detect UHE CR sources (see e.g. [3] for a review). As a byproduct of these interactions, cosmogenic neutrinos with energies of several EeV are created.

Many ongoing and proposed experiments, such as IceCube [4], ARA [5], ARIANNA [6] and the Pierre Auger Observatory [7], have capabilities to search for these cosmogenic neutrinos. To date, we are still awaiting a first detection. An original approach is pursued by the ANITA collaboration, who operate a suborbital balloon flying above Antarctica [8]. During each flight which lasts about a month, the polarization antennas mounted on this balloon observe a large portion of the Earth surface, searching for transient signals consistent with those predicted from neutrino-induced particle showers. From the data collected during the first two flights, ANITA collaboration sets the tightest constraints on the neutrino flux at energies above about 40 EeV [4, 9].

As pointed out in [10], the ANITA balloon can also serve as an UHECR detector by detecting the radio signal emitted by the UHECR atmospheric showers. During the first flight, 16 such events were detected with polarization consistent with a geomagnetic origin of the signal. Among these events, 14 were seen after reflection off the ice surface of the continent while 2 events were seen directly, without reflection on the surface. In the second flight of the balloon, a new "direct event" was observed [11].

In a recent reanalysis of the data [11], the ANITA collaboration found an additional event (event 3985267) which shares some properties of the signals emitted by the atmospheric showers. The detected electric field was predominantly horizontally polarized, with the polarization direction consistent with the geomagnetic origin of the emission [12]. Its waveform does not correlate well with the reflected CR signal, which is why it was neglected in the previous analyses. The waveform of the event can be interpreted as coming from an atmospheric shower observed directly because it lacks the change of sign in the polarization expected for a signal from a cosmic-ray induced shower reflected in the ice at a large zenith angle. However, this interpretation faces difficulties as the signal arrives from a direction which is 27.4° below the horizontal. The geomagnetic radio emission from an air shower is known to be beamed roughly in the direction of the incoming primary particle [12] and the shower would then have to be initiated by a particle which has crossed through a significant portion of the Earth. Neutrinos are the only known particles capable of doing this. The authors of [11] considered the case of a τ neutrino producing a τ lepton which then decays in the atmosphere and initiates an atmospheric shower, but found that the probability of this occurring is suppressed by a factor $\sim 4 \cdot 10^{-6}$ due to neutrino absorption in the Earth induced by the large neutrino interaction cross section at EeV energies. Anthropogenic origin for the event was found to be rather strongly disfavored by the data.

Recently, we investigated transition radiation (TR) from particle showers crossing the interface between dense media and air [13]. It was found that the signal is typically emitted into a wide solid angle and is coherent up to frequencies of several GHz. Because of this broad emission, the signal seen at 27.4° below the horizon could be explained as transition radiation from an Earth-skimming neutrino, avoiding the large suppression due to neutrino absorption in the Earth at EeV energies. In this paper we investigate whether it is realistic that the upcoming ANITA event was caused by transition radiation emitted by a neutrino-induced shower which starts its development in ice and then crosses into the atmosphere. While the transition radiation signal is about an order of magnitude weaker than the Askaryan emission, the additional solid angle might explain why the first detection of a $\sim$ EeV neutrino could occur through transition radiation.

In the first part of the paper we discuss whether it is possible to explain the parameters of the observed ANITA event in terms of transition radiation. In the

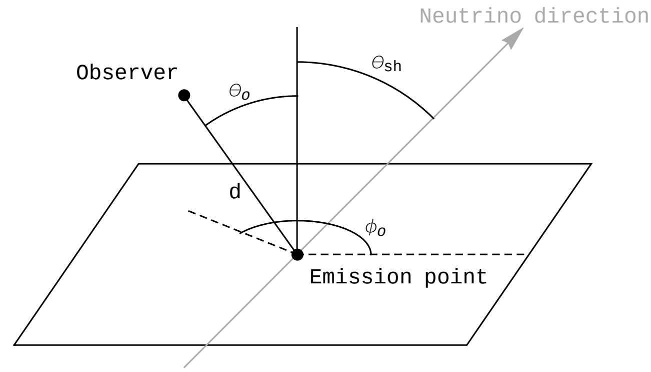

FIG. 1. Sketch of the emission geometry. The neutrino moves along a trajectory (gray arrow) described by a zenith angle $\theta_{\rm sh}$ from the vertical; the emission point is at the intersect of this trajectory with the Earth's surface. The observer is located at distance d from the emission point at zenith angle θ_o. Projections of neutrino and observer directions into the horizontal plane are displayed with dashed lines; the angle between them is ϕ_o.

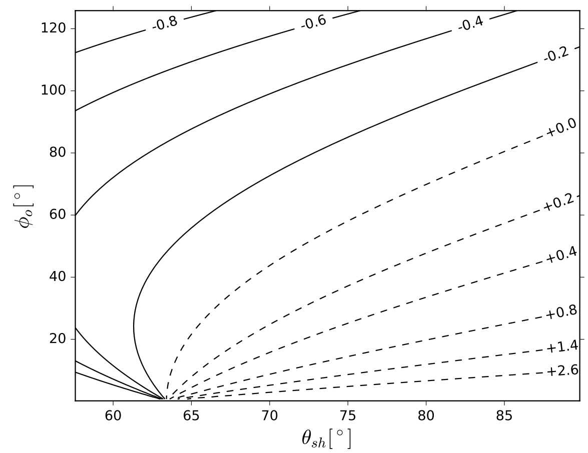

FIG. 2. Approximate degree of polarization of the signal A_V/A_H defined in Eq. (6) as a function of the neutrino inclination $\theta_{\rm sh}$ and the observer position ϕ_o (see Fig 1); using fixed $\theta_o = 63.2^\circ$ determined by the data. Only portion of the parameter space in agreement with the measured values $A_V/A_H \approx 0.2$ is shown.

second part we then place a conservative upper limit on the exposure of the ANITA balloon to this kind of events and compare it with exposures of other experiments. We conclude by discussing our findings.

II. CAN TRANSITION RADIATION EXPLAIN THE MAIN FEATURES OF THE EVENT?

In this section we evaluate whether it is in principle possible to explain the observed upward-going event in terms of TR. We work with the approximation of a spherical Earth of radius $R = 6373\,\text{km}$ and the height of the balloon above the surface $h = 34\,\text{km}$. Given the order-of-estimate nature of our arguments we will not discuss uncertainties.

A. Geometry

Assuming a transition radiation origin of the signal, we have to locate its emission on the Earth's surface. Given the distance to the balloon, we will approximate the emission as coming from a single point, neglecting its spatial extent. For the ANITA upcoming event, the observer's zenith angle θ_o shown in the sketch in Fig. 1 can be calculated from simple trigonometry giving $\theta_o = 63.2^\circ$. This corresponds to a distance d between the balloon and the emission point (see Fig. 1) of about $d \approx 75\,\text{km}$.

The remaining two angles describing the geometry — the neutrino zenith angle $\theta_{\rm sh}$ and the azimuth ϕ_o between the observer and the neutrino directions (Fig. 1) — can be constrained using the polarization of the signal. It is a sensible approximation that most of the shower particles are moving in the direction of the incoming neutrino

$$\hat{\boldsymbol{v}} \sim (\sin\theta_{\rm sh}, 0, \cos\theta_{\rm sh})\,. \tag{1}$$

Emission in the observer direction

$$\hat{\boldsymbol{k}} = (\sin\theta_o\cos\phi_o, \sin\theta_o\sin\phi_o, \cos\theta_o) \tag{2}$$

is in such case polarized as [13]

$$\boldsymbol{E} \sim \boldsymbol{v}_\perp = \hat{\boldsymbol{k}} \times \left(\hat{\boldsymbol{v}} \times \hat{\boldsymbol{k}}\right). \tag{3}$$

The electric field $\boldsymbol{E}$ is projected onto two orthogonal directions given by vectors

$$\boldsymbol{e_V} = (\cos\theta_o\cos\phi_o, \cos\theta_o\sin\phi_o, -\sin\theta_o) \tag{4}$$

and

$$\boldsymbol{e_H} = (\sin\phi_o, -\cos\phi_o, 0)\,, \tag{5}$$

the latter in a horizontal direction. We can then quantify the ratio of the two polarizations expected for the signal defined here as

$$\frac{A_V}{A_H} = \frac{\boldsymbol{e_V}\cdot\boldsymbol{v}_\perp}{\boldsymbol{e_H}\cdot\boldsymbol{v}_\perp}. \tag{6}$$

In Fig. 2 we show the polarization ratio as a function of $\theta_{\rm sh}$ and ϕ_o for the known value of θ_o.

From Figure 1 of paper [11], the ratio of strengths of the vertical and horizontal polarizations is approximately $A_V/A_H \approx 0.2$, using the relative magnitudes of the components of the electric field at the time of its maximal magnitude. As shown in Figure 2 there are combinations of $(\theta_{\rm sh},\ \phi_o)$ for which the polarization fraction predicted by the TR model matches the experimental data. The observed degree of polarization can be explained if $\theta_{\rm sh}$ is large, typically $> 65°$. This agrees with the interpretation of the ANITA detected event as being Earth-skimming. Also as both senses of polarity are possible, TR does not suffer from the sign mismatch which disfavors the explanation of the detected event as a reflected UHECR signal.

B. Energy

We can use the knowledge of the observed peak electric field $E_{\rm max} \sim 5 \cdot 10^{-4}\,{\rm V/m}$ to put an approximate lower bound on the neutrino energy. ANITA detects signals between 200 MHz and 1200 MHz [10], corresponding to a bandwidth of $\Delta f = 1000\,{\rm MHz}$. Assuming a mostly flat spectrum in the frequency domain with amplitude E_ω, the peak value of the observed signal would correspond to

$$E_\omega \approx 5 \cdot 10^{-7}\,{\rm V/m/MHz} \tag{7}$$

in the convention of [13]. The signal strength decreases proportionally with the distance between emission and observation. For the determined observer - emission distance $d \sim 75$ km, this corresponds to a distance-independent measure of the emission strength

$$E_\omega d \approx 37.5\,{\rm mV/MHz}. \tag{8}$$

In the following we will consider the cases of purely hadronic showers induced by all flavors of neutrinos in neutral current (NC) interactions, and by tau and muon neutrinos in charged current (CC) interactions (neglecting the showers induced by the tau and muon lepton - see below), as well as electromagnetic+hadronic showers induced by electron neutrinos in CC interactions. In [13] it was shown that the amplitude of the electric field due to TR approximately scales with the shower energy for energies in the range of 1 to 100 TeV, but at 1 EeV this scaling was broken because of the Landau-Pomeranchuk-Migdal effect (LPM) [14]. This effect dramatically reduces the probability of interaction of electrons and positrons at the highest energies, leading to elongation of electromagnetic (sub-)showers. Due to the elongation, the number of particles present at the shower maximum is reduced and the TR signal is diminished proportionally. Simulations show that the integral of the number of electrons over shower length scales very accurately with energy [15]; this is why the number of particles at shower maximum typically scales with the shower energy when there is no LPM effect. When the LPM effect takes place, an increase in the shower length must be accompanied by a corresponding decrease in the average number of particles at shower maximum. In the following we adopt a simple model in which the product of the shower length and the number of particles at shower maximum scales linearly with shower energy. The TR emission is proportional to the electron excess [13], which is approximately a constant fraction (of order 25% in ice) of the total number of electrons and positrons[*1].

For electromagnetic showers at EeV energies, we will model the shower length, defined as the length of the shower over which the number of particles remains above half the value at maximum, as

$$L_{\rm sh,em} = 25 \left(\frac{E_{\rm sh}}{\rm EeV}\right)^{1/3} {\rm m}. \tag{9}$$

This parametrization is taken from [16], where both the LPM effect and the photonuclear cross section are accounted for showers simulated in rock. The given parameterization has been corrected for ice. The radiation length X_0 in ice is a factor of four larger [17] and the energy above which the showers start to increase in length increases also by a factor of 4. These effects go in the opposite directions and overall one expects showers in ice to be ~ 2 times longer than in rock. However, in addition in Ref. [16] the definition of shower length requires the number of electrons to exceed only 1/10 of the maximum. A reduction in shower length of about a factor of two can be expected from changing the definition of shower length from 1/10 to 1/2 [18], which should better describe our situation and bring the shower length back to (9). In any case, the main conclusion of this work does not change if we increase or decrease the above factor by two or if we change the exponent to 1/2 as suggested by an analytic model [19] using a different definition of shower length. For our purposes, using (9) to model shower length of an electromagnetic shower in ice is thus sufficiently accurate.

Based on these considerations of shower length, we model the TR signal coming from electromagnetic showers to scale with shower energy as $E_{\rm sh}^{2/3}$ to keep the product of shower length and number of particles at maximum linearly proportional to $E_{\rm sh}$, as discussed above. The largest value of $E_\omega d$ observed for a vertical EeV electron-induced shower in our previous simulations [13] was $1.5\,{\rm mV/MHz}$. We will thus take this value as a maximal attainable strength of a TR signal from an EeV shower and extrapolate this value to higher energies as

$$\langle E_\omega d\rangle_{\rm em}^{\rm max} = 1.5 \left(\frac{E_{\rm sh}}{\rm EeV}\right)^{2/3} \frac{\rm mV}{\rm MHz}. \tag{10}$$

On the other hand, the length of the hadronic showers are mostly unaffected by the LPM effect because the hadronic interactions of the shower particles rapidly degrade the energy before high energy electrons and photons are produced. The shower length rises by only about 20% as the primary shower energy rises from 10 PeV to 10

[*1] The maximal achievable amplitude of the TR signal is thus proportional to the maximum number of particles at shower maximum [13].

EeV [20]. We then model the shower length of hadronic showers as constant

$$L_{\mathrm{sh,had}} = 5\,\mathrm{m}. \tag{11}$$

Following the same reasoning as before we assume that the TR signal scales linearly with the shower energy. Again, our final conclusions are mostly insensitive to the particular value of $L_{\mathrm{sh,had}}$. For low energies an electron-induced shower is assumed to be a good proxy for a hadronic shower of the same energy as most of the energy of both electromagnetic and hadronic showers is ultimately dissipated in electromagnetic processes and the number of particles at maximum are similar [20]. Using the maximal achievable value of the distance-scaled TR electric field $6.4{\cdot}10^{-4}$ mV/MHz for a 100 TeV electromagnetic shower found in [13] and extrapolating it linearly with shower energy we obtain

$$\langle E_\omega d\rangle^{\max}_{\mathrm{had}} = 6.4\left(\frac{E_{\mathrm{sh}}}{\mathrm{EeV}}\right)\frac{\mathrm{mV}}{\mathrm{MHz}}. \tag{12}$$

Note that we can not extrapolate the result from the EeV simulations here, because those are already affected by the LPM effect. The result in (12) represents the highest achievable signal from a hadronic shower of energy below about 100 EeV at which the LPM effect is not expected to affect the shower length and it applies for showers which cross the ice-air boundary at around the shower maximum. Showers which cross away from the shower maximum would have their signal diminished.

All three neutrino flavors can interact through NC and CC interactions. In the former, the breakup of the nucleon induces a hadronic shower that typically carries 20% of the incoming neutrino energy. With the signal strength (12) we then need at least a neutrino of energy $E_\nu \simeq 30$ EeV to produce the emission seen in ANITA. We stress out that this lower bound on the energy – and those which follow – was obtained by extrapolating simulation results of lower energy showers to showers initiated by ∼20-30 EeV particles, which are computationally expensive to simulate. This bound thus serves only as a rough estimate of neutrino energies necessary to produce the detected signal.

The outcome of the CC interactions depends on the neutrino flavor. Charged current interactions of the electron neutrino produce two showers, one electromagnetic and one hadronic carrying about 80% respectively 20% of the total energy [21]. When this neutrino interacts very close to the surface such that both showers cross the interface with significant numbers of particles, the signal strength can be up to

$$\langle E_\omega d\rangle^{\max} = \left(6.4\left(\frac{0.2E_\nu}{\mathrm{EeV}}\right) + 1.5\left(\frac{0.8E_\nu}{\mathrm{EeV}}\right)^{2/3}\right)\frac{\mathrm{mV}}{\mathrm{MHz}}. \tag{13}$$

Thanks to the electromagnetic contribution, the minimal neutrino energy now decreases to $E_\nu \simeq 20$ EeV.

Charged interactions of tau and muon neutrinos produce a hadronic shower carrying again about 20% of the neutrino energy and an outgoing lepton. The muon lepton gradually loses its energy through stochastic processes that induce many low energy showers over a very long path length [22]. They can be discarded in this work, because the number of particles in these showers, $\simeq 3\cdot 10^{-5}(E_\mu/1\,\mathrm{GeV})$ [22], is very small compared to those necessary to produce a sizable radio signal. Before decaying, the muon typically loses most of its energy through ionization and stochastic processes and it does not produce a significant electromagnetic shower on its decay. We thus assume only the hadronic shower from CC interactions of muon neutrino can be detected.

The behavior of the tau lepton produced at the neutrino interaction vertex can in principle be different as tau lepton has a shorter lifetime than muon. However, a 10 EeV tau lepton with a decay length of ∼500 km loses half of its energy in about 5 km of ice through stochastic processes (using the analytic model III of [23]). For those energies only about 1% of the tau decays would induce a large enough shower to produce a TR signal comparable to the observed signal. The contribution of tau neutrino CC interactions are thus subdominant and will be neglected. Only the hadronic shower from CC interactions of tau neutrino will be considered. In both ν_μ and ν_τ CC interactions, the minimal neutrino energy necessary to produce detectable signal is therefore $E_\nu \simeq 30$ EeV.

We conclude that transition radiation from a neutrino-induced shower can in principle explain the main characteristics of the observed signal for neutrino energies $E_\nu \sim 20 - 30$ EeV or higher. It is known that for these extreme energies, neutrinos are absorbed in the Earth unless their zenith angles are very close to horizontal, $\theta_{\mathrm{sh}} \approx 90^\circ$ [24]. However, because of the wide angular emission of transition radiation, Earth-skimming neutrinos can induce a signal which is seen at a large angle below the horizon.

The fact that the detectable neutrinos by means of TR have to be Earth-skimming would help in diminishing the uncertainty on the direction of the incoming neutrino as determined from Fig. 2, leading to a pointing resolution of a few degrees. On the other hand, there is a degeneracy between the neutrino energy and the stage of the shower development at which the shower crosses the boundary [13], leading to a poor energy resolution.

III. FLUX CONSTRAINTS

Having determined that transition radiation can be responsible for the observed ANITA event, we evaluate whether the neutrino flux necessary to explain the event in terms of TR satisfies the current experimental limits. We do so in the current section by estimating an upper limit on the exposure achieved by the ANITA balloon for observation of TR events and comparing it with the exposures from other experiments.

The three neutrino flavors and their NC and CC interactions represent six channels which can lead to an experimental signal. They are independent and the relevant calculations are very similar (or identical) for all six cases. We thus first present in greater detail the calculation of the exposure for the NC interaction of any of the flavors and later comment on how the calculation has been altered to accommodate the CC interactions.

A. Neutral current interaction

The number of NC interaction events of any given neutrino flavor detected by the experiment is a Poisson random variable. Its expectation value is expressed by an integral over the neutrino energy

$$\langle N \rangle = T \int dE_\nu \, F(E_\nu) A(E_\nu), \quad (14)$$

where T is the duration of the measurement, $F(E_\nu)$ is the energy-dependent flux of neutrinos and $A(E_\nu)$ is the aperture of the experiment.

The aperture of the ANITA experiment for TR detection can be written as

$$A(E_\nu) = \int_{S_{\rm eff}(E_\nu)} dS \int_{\rm up-going} d\Omega \; p_{\rm det} \cos\theta_{\rm sh}. \quad (15)$$

Here we integrate the probability $p_{\rm det}$ that the experiment detects a particular neutrino described by its direction and point at which its trajectory leaves the Earth[*2]. The angular integral goes over half of the sky to capture only the up-going neutrinos. The outer integral goes over the surface of the Earth which is visible from the balloon and that is close enough such that the detection is in principle possible (see further). The additional factor of $\cos\theta_{\rm sh}$, where $\theta_{\rm sh}$ is the angle between the surface normal and the neutrino direction, represents the attenuation of the neutrino flux due to the projection of the surface as seen by the neutrinos.

The probability $p_{\rm det}$ has three components

$$p_{\rm det} = p_t \cdot p_i \cdot p_p, \quad (16)$$

each assuming that the previous process occurred successfully:

- Probability p_t for the neutrino to cross through the Earth.
- Probability p_i for it to interact close enough to the surface so that the induced shower crosses the interface and produces sufficiently strong transition radiation at least in some directions on the sky.
- Probability p_p to have the balloon placed at a position where the transition radiation is sizeable.

The probability for a given neutrino to go through the Earth is related to the total neutrino interaction cross section on nucleons σ_T [21], and the number density of nucleons given by the density of Earth at distance r from the center $\rho(r)$ divided by the nucleon mass M_n [24]. We model the Earth as having an additional 2 km layer of ice with density $\rho_{\rm ice} = 0.924\,{\rm g/cm^3}$ to account for Antarctic ice; the Earth radius R includes height of this ice cap. The probability can be then calculated as

$$p_t = \exp\left(-\frac{\sigma_T}{M_n} \int_{-R\cos\theta_{\rm sh}}^{R\cos\theta_{\rm sh}} \rho\left(\sqrt{R^2 \sin^2\theta_{\rm sh} + l^2}\right) dl \right), \quad (17)$$

where the integral in l goes along the neutrino trajectory within the Earth. Notice that the probability depends implicitly on the neutrino energy through σ_T and explicitly on the neutrino inclination $\theta_{\rm sh}$. For neutrinos of EeV energies p_t is practically zero except for a small solid angle region a few degrees away from $\theta_{\rm sh} = 90°$.

For transition radiation to be sizeable, we need the shower to leave the ice at a point where the shower contains a large number of particles. Because of this, we model the probability for a sufficiently close interaction as

$$p_i = \frac{L_{\rm sh,had}\,\sigma_{NC}\,\rho_{\rm ice}}{M_n}, \quad (18)$$

which is the probability for the neutrino to interact through a NC interaction in a length comparable to the longitudinal dimension $L_{\rm sh,had}$ of the hadronic shower created by this interaction (11). Here σ_{NC} is the neutrino cross section for NC interaction on nucleons.

From our previous discussion we know that for a 1 EeV neutrino the transition radiation is not strong enough to produce a signal above the ANITA threshold which can be estimated to be $E_{\rm thr} \approx 150\,\mu{\rm V/m}$. This magnitude can be obtained considering the lowest pulse amplitude of the four published events [11] and dividing it by a factor of order two. This is close to an estimate obtained for a horn antenna of central frequency 600 MHz if we conservatively consider a detection threshold of 2.3 times the lowest RMS noise voltage of 10 μV quoted for ANITA [8]. Assuming linear scaling of the radiated electric-field with energy and taking into account that only about 20% of the neutrino energy goes into the shower, the maximal distance at which TR emission of any given shower can be detected is

$$D \approx 8.5 \left(\frac{E_\nu}{\rm EeV}\right) \,{\rm km}. \quad (19)$$

This sets a cutoff for the lowest theoretically detectable neutrino energy at ~ 4 EeV, and this value would only apply for vertical emission.

Finally, assuming the neutrino crosses through the Earth and interacts sufficiently close to the surface at

[*2] Or possibly its extension if the neutrino interacts before the crossing point.

a point which is at a distance smaller than $D(E_\nu)$ from the balloon, we will assume that the ensuing emission is detectable from any point in the sky, $p_p = 1$. This is not a realistic assumption as for very inclined showers the emission is far from being isotropic [13]. We expect this overestimates the calculated aperture by about a factor of 4-5, however this assumption vastly simplifies the calculations and is sufficient to lead to physically relevant conclusions. Additionally, the ANITA experiment can not detect signals from too close to the payload as its antennas are observing the horizon. Neglecting this effect as we do increases the obtained aperture and thus leads to an even more conservative upper bound.

With all these assumptions, the expression for the aperture decouples into

$$A = \left(\int_{S_{\rm eff}(E_\nu)} dS\right)\left(\int_{\rm up-going} p_i p_t \cos\theta_{\rm sh}\, d\Omega\right) \quad (20)$$

as p_p then depends only on the point where neutrino trajectory leaves the Earth and p_t, p_i depend only on the neutrino direction relative to the ground. The first integral evaluates to the area which is visible from the balloon and which is closer than $D(E_\nu)$. A straightforward calculation leads to

$$\int_{S_{\rm eff}(E_\nu)} dS = \begin{cases} 0, & E_\nu < 4\,\mathrm{EeV} \\ \frac{2\pi R^2 h}{R+h}, & E_\nu > 77\,\mathrm{EeV} \\ \frac{\pi R}{R+h}\left[D(E_\nu)^2 - h^2\right], & \text{otherwise} \end{cases} . \quad (21)$$

At the lowest energies the effective detection area is zero because the showers do not have enough energy to produce a detectable electric field. At the highest energies the whole patch of the Earth of area $1.35 \cdot 10^6\,\mathrm{km}^2$ which is observable from the balloon is sufficiently close to ascertain a detection. Intermediate energies interpolate between these two limits.

The second integral in (20) can be rewritten as

$$\Omega_{\rm eff} = \int_{\rm up-going} p_i p_t \cos\theta_{\rm sh}\, d\Omega \quad (22)$$

$$= 2\pi \int_0^1 p_i p_t \cos\theta_{\rm sh}\, d(\cos\theta_{\rm sh}). \quad (23)$$

Using the known neutrino cross sections and density profile, we can evaluate this integral numerically.

With known $S_{\rm eff}$ and $\Omega_{\rm eff}$ we can calculate the exposure $T_a A$ from the total live time $T_a = 45.8$ days of the two ANITA flights [9, 25]. The result is plotted in Fig. 3.

B. Charged current interactions

As discussed previously, the hadronic showers from CC interactions of tau and muon neutrinos are expected to produce significant contributions to the number of detected events. This allows us to directly use the results of the previous section, after replacing the NC interaction cross section in Eq. (18) with the CC one.

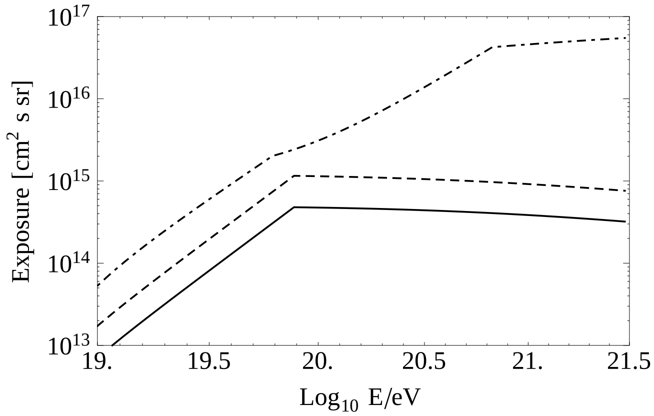

FIG. 3. Contributions to the conservative upper limit on the exposure for TR detection from neutral current interaction (solid) and charged current interaction of ν_τ, ν_μ (dashed) and ν_e (dot dashed); each curve represents a contribution of a single flavor.

For the electron neutrino, two showers are produced as discussed in the first section of the paper and this requires a slightly more involved approach. When the neutrino interacts very close to the surface, both these showers cross the surface and their emission adds. Following our strategy of overestimating the aperture we assume they add coherently, leading to the TR signal in Eq. (13). For this to happen, the neutrino has to interact in a length roughly $L_{\rm sh,had}$. In addition, there is a possibility that the neutrino interacts in such a way that the electromagnetic shower elongated by the LPM effect reaches the boundary, but the shorter hadronic shower does not. The length corresponding to this situation is approximately $L_{\rm sh,em} - L_{\rm sh,had}$ and the emitted TR in this case is just the second term in (13). Using again the cross section for CC interaction in Eq. (18), we can evaluate the corresponding exposure for CC interaction of ν_e in a way analogous to the previous section.

The energy dependence of the exposure from CC interactions is shown in Fig. 3. The CC interactions of ν_μ, ν_τ lead to a higher exposure than the NC interactions due to higher cross section for CC interactions. Charged current interactions of ν_e are largest everywhere due to the additional electromagnetic contribution. This contribution dominates above 10^{20} eV because of the increased length of the electromagnetic shower.

C. Total exposure

Adding the contributions plotted in Fig. 3 for all six combinations of flavor and interaction channels, an upper limit for the total exposure of the two first ANITA flights for neutrino detection with the TR is plotted in Fig. 4.

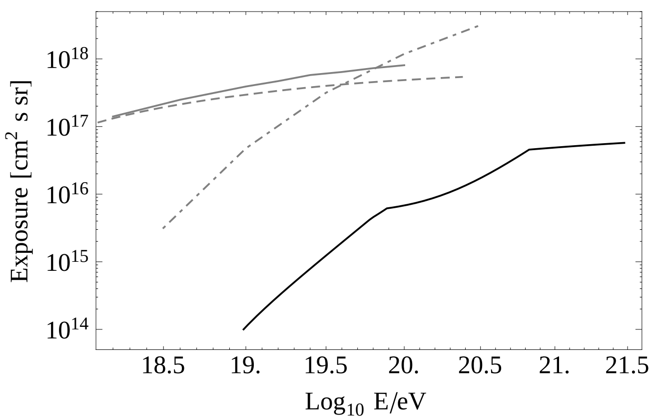

FIG. 4. Conservative upper limit on the exposure of the two combined ANITA flights for neutrino detection using TR (black), compared with exposures of other experiments (gray): standard analysis of ANITA using Askaryan radiation [26] (dot-dashed), Pierre Auger Observatory [7] (dashed), IceCube [4, 27] (solid).

In the same plot we also display the exposures of other experiments searching for cosmogenic neutrinos: the analysis of ANITA when trying to detect Askaryan radiation from neutrino-induced showers in ice [26], assuming the same live time T_a; approximately nine years of data collected at the Pierre Auger Observatory [7]; and preliminary results of six years of IceCube [4]. For IceCube we used the neutrino effective area from [27] with data taken in several periods of time with various string configurations [4, 27].

IV. DISCUSSION

In this paper we evaluated the possibility that the signal of an unknown origin detected by the ANITA collaboration is a transition radiation from a shower induced by a high-energy neutrino. While the properties of the observed signal can in principle be explained with a transition radiation origin for the signal, the flux necessary for successful explanation is in tension with the current best limits from the Pierre Auger observatory, IceCube and ANITA. In a conservative analysis we found that the exposure for the TR signal is at least two orders of magnitude smaller than the exposure collected by ANITA at the energies necessary to explain the event in terms of transition radiation; this exposure is also smaller than extrapolations of the Pierre Auger and IceCube exposures to these energies. The probability that ANITA detected transition radiation induced by a cosmogenic neutrino shower and none of the other experiments detected any neutrino event is thus negligible.

Our analysis of the aperture of the experiment for the TR signal was optimistic by assuming fully isotropic emission. Moreover, due to its experimental design ANITA cannot observe signals produced right below the payload, but this was ignored in the exposure estimate. In reality, the exposure for a TR detection by the ANITA balloon is significantly smaller, further decreasing the probability of a TR explanation of the ANITA event.

From a comparison of the exposures of the TR signal with the standard ANITA analysis we also see that TR is not a viable alternative for this particular geometry and presents less than $\sim$1% correction to the exposure. This is caused by the fact that the traditional Askaryan emission searched for by ANITA is stronger than transition radiation. Moreover the detection technique exploiting the Askaryan radiation benefits from the fact that a detectable neutrino interaction can occur at distances of $\sim$ km from the ice-air interface and not only close to the surface, further disfavoring the transition radiation. This however does not mean that for a different geometry — such as a ground array — TR does not pose a viable method of detection and further studies in this direction are necessary.

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[1] J. Abraham *et al.* (Pierre Auger), Phys.Lett. **B685**, 239 (2010), arXiv:1002.1975 [astro-ph.HE].

[2] M. Fukushima (Telescope Array), (2015), arXiv:1503.06961 [astro-ph.HE].

[3] A. A. Watson, Rept. Prog. Phys. **77**, 036901 (2014), arXiv:1310.0325 [astro-ph.HE].

[4] M. G. Aartsen *et al.* (IceCube), in *Proceedings, 34th International Cosmic Ray Conference (ICRC 2015)* (2015) arXiv:1510.05223 [astro-ph.HE].

[5] P. Allison *et al.*, Astropart. Phys. **35**, 457 (2012), arXiv:1105.2854 [astro-ph.IM].

[6] S. W. Barwick *et al.* (ARIANNA), Astropart. Phys. **70**,

12 (2015), arXiv:1410.7352 [astro-ph.HE].

[7] A. Aab *et al.* (Pierre Auger), Phys. Rev. **D91**, 092008 (2015), arXiv:1504.05397 [astro-ph.HE].

[8] P. W. Gorham *et al.* (ANITA), Astropart. Phys. **32**, 10 (2009), arXiv:0812.1920 [astro-ph].

[9] P. W. Gorham *et al.* (ANITA), Phys. Rev. **D82**, 022004 (2010), [Erratum: Phys. Rev.D85,049901(2012)], arXiv:1011.5004 [astro-ph.HE].

[10] S. Hoover *et al.* (ANITA), Phys. Rev. Lett. **105**, 151101 (2010), arXiv:1005.0035 [astro-ph.HE].

[11] P. W. Gorham *et al.*, Phys. Rev. Lett. **117**, 071101 (2016), arXiv:1603.05218 [astro-ph.HE].

[12] T. Huege, Phys. Rept. **620**, 1 (2016), arXiv:1601.07426 [astro-ph.IM].

[13] P. Motloch, J. Alvarez-Muñiz, P. Privitera, and E. Zas, Phys. Rev. **D93**, 043010 (2016), arXiv:1509.01584 [astro-ph.HE].

[14] L. D. Landau and I. Pomeranchuk, Dokl. Akad. Nauk Ser. Fiz. **92**, 535 (1953).

[15] E. Zas, F. Halzen, and T. Stanev, Phys. Rev. **D45**, 362 (1992).

[16] M. Tartare, D. Lebrun, and F. Montanet, Phys. Rev. **D86**, 033005 (2012), arXiv:1211.6992 [hep-ph].

[17] C. Patrignani *et al.* (Particle Data Group), Chin. Phys. **C40**, 100001 (2016).

[18] J. Alvarez-Muniz and E. Zas, Phys. Lett. **B411**, 218 (1997), arXiv:astro-ph/9706064 [astro-ph].

[19] L. Gerhardt and S. R. Klein, Phys. Rev. **D82**, 074017 (2010), arXiv:1007.0039 [hep-ph].

[20] J. Alvarez-Muniz and E. Zas, Phys. Lett. **B434**, 396 (1998), arXiv:astro-ph/9806098 [astro-ph].

[21] A. Connolly, R. S. Thorne, and D. Waters, Phys. Rev. **D83**, 113009 (2011), arXiv:1102.0691 [hep-ph].

[22] T. Stanev and C. P. Vankov, Phys. Rev. **D40**, 1472 (1989).

[23] S. I. Dutta, Y. Huang, and M. H. Reno, Phys. Rev. **D72**, 013005 (2005), arXiv:hep-ph/0504208 [hep-ph].

[24] R. Gandhi, C. Quigg, M. H. Reno, and I. Sarcevic, Astropart. Phys. **5**, 81 (1996), arXiv:hep-ph/9512364 [hep-ph].

[25] P. W. Gorham *et al.* (ANITA), Phys. Rev. Lett. **103**, 051103 (2009), arXiv:0812.2715 [astro-ph].

[26] M. J. Mottram, *A Search for Ultra-high Energy Neutrinos and Cosmic-Rays with ANITA-2*, Ph.D. thesis, University Coll. London (2012).

[27] M. G. Aartsen *et al.* (IceCube), Phys. Rev. **D88**, 112008 (2013), arXiv:1310.5477 [astro-ph.HE].