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Tau lepton fluxes in underground salt dome

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Ultrahigh-energy neutrino originated from the GZK effect is the most plausible source for high energy neutrinos. However, their small flux and low interaction probability make their detection very challenging. To have a proper event rate, the interaction volume must be much larger than the km^3-size detector currently under construction. One of the alternative techniques resorts to the detection of coherent radio waves produced inside an underground salt dome. We have developed a Monte-Carlo simulation code for the interactions and propagations of leptons inside the Earth. In this code, the Earth is treated as a three-layer sphere consisting of iron in the core, standard rock in the mantle and water on the surface. We have also added salt as the fourth material surrounding the detector. The energy loss of muons and tau leptons in salt are calculated. To simulate a 100-km^3 water-equivalent target volume, we employ a spherical sphere salt dome of 5 km in radius. The tau lepton fluxes .

1. Introduction

Ultra-high energy cosmic rays have been observed since the 1960s. The existence or absence of GZK cutoff has been a major debate between two experimental groups, AGASA and HiRes, in the last decades. With or without GZK cutoff, the byproducts of $p + \gamma_{\text{CMB}}$ interaction will always produce ultrahigh-energy neutrinos (> EeV) (UHE-ν). This is the most certain source of high-energy neutrinos and neutrino telescopes are constructed for their detections. However, the GZK-neutrino flux is too weak for detectors of km^3 water-equivalent size, such as IceCube[1] or KM3NeT[2] to detect. To have a reasonable event rate of 1 event/year, an acceptance in the order of 100 km^2 sr is required [3]. Owing to the high construction cost, it is not feasible to install a PMT-based detector in such a large volume.

Alternative approaches have been proposed. One is the extension of the air shower experiments utilizing the Earth-skimming neutrinos. Showers initiated by decay of tau leptons, which are produced by charged current interaction inside the Earth. Showers can be detected by Cherenkov [4] and/or fluorescence [5] light detector similar to HiRes. A major breakthrough in shower detection technology is the radio detection by Askaryan effect [6], which provides a new method for detecting UHE-ν. Some preliminary studies (ANITA, Goldstone, RICE [7]) are currently conducted. The cost of building a radio array in underground neutrino telescope is greatly reduced, which make it more attractive for Mega-ton detector. A possible site for such an experiment is an underground salt dome, which provides better transparency to radio wave than ice. When designing a detector, the main issue is to understand how much volume is needed in order to have a proper event rate. Many similar studies were conducted with detectors installed in ice or water. In this study, we examine the tau leptons fluxes in an underground salt dome.

2. Simulation

Interactions between neutrinos and leptons were simulated with a Monte-Carlo program [8]. The charged and neutral current interactions take place inside the Earth, which is modeled with density and composition varying with geocentric distance. Lepton propagates with energy loss and/or decay/interaction. The UHE-ν fluxes [9] entered the Earth isotropically. Assuming full oscillation, ν_τ fluxes are taken as 1/2 of GZK ν_μ flux, which do not have oscillation effect.

Since detector array may detect events out side array, we define a Detector Sensitive Region (DSR). In this simulation, DSR is a sphere of radius 5 km and the center of sphere is at 6 km below mean sea level. Salt rock filled the DSR, while standard rock filled the exterior of DSR. So, the top of DSR is buried under 1 km of rock. The energy loss and range of tau-lepton in salt is calculate with mean A=29.2447, mean Z=13.5 , and density= 2.16532g/cm^3.

3. Results

We inject 10^7 ν_τ to DSR. At the time of this proceeding was written, 1.278×10^6 events were available for analysis. This number corresponds to 125 years of full-time operation. The energy of each event is sampled from GZK differential flux from 10^5 GeV to 10^{10} GeV. In total, 7957 tau-leptons arrived in DSR. The event rate is approximately 0.032 event/(km^2 sr yr).

When leptons enter DSR, we record their positions, directions, and related information for each interaction. The energy and cosine of zenith angle of tau-leptons entering DSR are shown in Figure 1. The energy spectrum and arrival directions are shown in Figure 2.

Most of these events (~87%) are down-going events with cosθ > 0. Although up-going events are fewer, (~ 13% of all events), they are not totally vanish due to regeneration process ($\nu_\tau \to \tau \to \nu_\tau$). Much fewer events (~ 0.36%) pass through the core of the Earth, where density is highest and range of tau-lepton is shorter by 60% than that in the standard rock. For those down-going events, their spectra are similar and concentrate in between 10^8 GeV to 10^9 GeV, while the up-going events mostly fall below 10^8 GeV, except some Earth-skimming events at $-0.1< \cos\theta <0$.

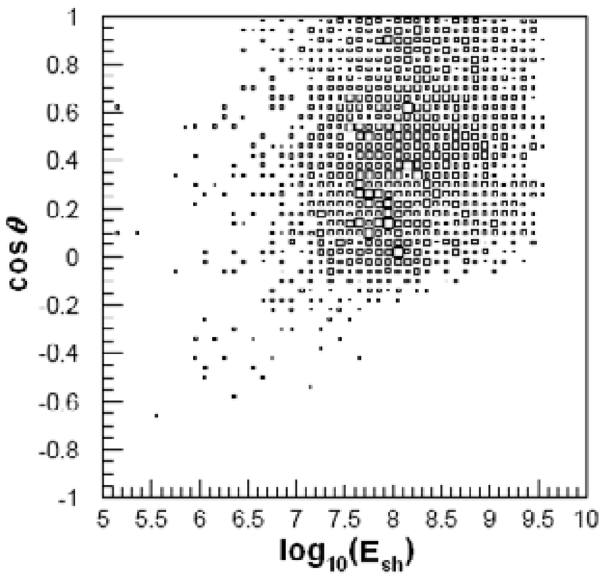

Figure 1. The energy and cosθ distribution for tau-leptons arrive in the simulated salt dome. Y axis, cosθ, is cosine of zenith angle of event arrival direction. Events coming from zenith have cosθ = +1. Up-going events have cosθ < 0. X axis is shower energy in the salt dome. The box size is proportional to the event number.

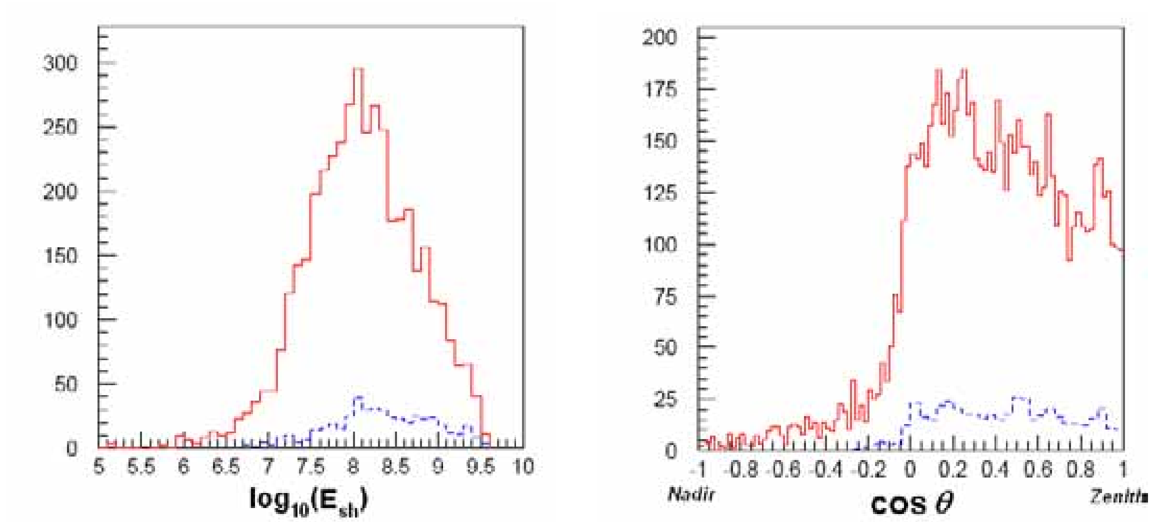

Figure 2. Shower energy and zenith angle distributions of tau-leptons. The solid red line is for all the events entering the 5 km radius sphere salt dome. The blue dash lines are the histograms of those shower triggered a simulated radio array as described below.

To estimate how many events can be observed, we use a simplified radio array as follows.

1. A radio array consists of 12×12 strings, each has 12 antenna. The spacing between antennas and between strings are 225 meter. The center of this cube array is at the center of DSR. The volume inside array is $(2.475\ \text{km})^3 = 15.16\ \text{km}^3$ or equivalent to $32.83\ \text{km}^3$ of water. However, the antenna can detect shower signal from outside this array.
2. Assume the attenuation length (λ) of radio signal in salt is 300 meter.
3. Instead of detail simulation of shower and radio signals, we simplified it to
$$\frac{dE_{hit}}{da} = \frac{E_{sh}}{2\pi r^2 \sin\alpha\Delta\alpha} e^{-r/\lambda}$$
Where r is the distance from shower maximum to antenna, dE_{hit}/da is the differential energy reach the detector, E_{sh} is the shower energy. The first division term is the equal partition of Cherenkov signal over a ring extend from shower axis by the Cherenkov angle α=65° and $d\alpha$=5°. The exponential term represent the absorption over distance r.
4. Antenna can be triggered if the differential energy received is greater than a minimum value dE_{mint}/da and antenna is within the Cherenkov ring. The minimum value dE_{mn}/da is defined as a threshold energy distributed over Cherenkov cone at one attenuation length away from shower maximum.
$$\frac{dE_{\min}}{da} = \frac{E_{th}}{2\pi\lambda^2 \sin\alpha\Delta\alpha} e^{-1}$$
5. To be able to re-construct event direction, a system-wide trigger must have at least 6 antennas triggered.

Event numbers of several threshold energies are compared in table 1. Example of $E_{th} = 10^6$ GeV is shown by the blue dash lines in Figure 2. The events are separated into 4 types, according to production of tau lepton by C.C. interaction and ending point where tau decays. Type 1 to 3 are listed in table 1, while type 4 events only pass through DSR and did not produced observable signals, therefore it is not included in Table 1.

Table 1. Event number per years for different thresholds and event types. Out/in mean interactions occurred outside/inside DSR. DB means detector detect two showers, subgroup of type 2. Notice that double bang event rate drop to 0 when the threshold energy increase to 10^7 GeV.

Type	CC	τ decay	All events	E_{th}		
				10^6 GeV	3×10^6 GeV	10^7 GeV
1	out	in	12.2 ± 0.3	0.38±0.05	0.20±0.04	0.10±0.03
2	in	in	12.1 ± 0.3	0.64±0.07	0.33±0.05	0.13±0.03
3	in	out	20.93 ± 0.4	1.49±0.11	1.11±0.09	0.60±0.07
DB	in	in	12.1 ± 0.3	0.07±0.02	0.02±0.01	0.00±0.00
Total (type 1,2,3)			63.7 ± 0.7	2.58±0.14	1.66±0.12	0.83±0.08

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4. Conclusions

We study the tau leptons flux in an underground salt dome, a sphere of radius 5 km buried under 1 km or standard rock. 1.278×10^6 tau neutrinos are injected to Salt dome and 7957 tau-leptons are produced inside this sphere. The equivalent operation time is 125 years and the event rate is approximately 0.032 event/(km^2 sr yr).

Based on the energy distribution in Figure2, the energy sensitive range of SalSA should be above 10^8 GeV. A simplified detector simulation of (2.475 km)^3 radio antenna array were used to study possible event rate. At threshold energy of 10^6 GeV, the tau lepton event rate is around 2.6 event/year. However, the real event number depends on the detail of detector. This study may provide front-end data for detailed simulation and optimization of detector design. Another important issue of tau lepton is the double bang signature. The range of tau-lepton is 3.4 km to 11 km [8] in the optimal energy range. Most of these events would not produce the double bang signature of tau-leptons. It is necessary to low energy threshold to 3×10^7 GeV, where tau-lepton range drop down to 1 km.

5. Acknowledgements

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