Calculated spectrum of muon-induced cascades at great depths of water or ice

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Introduction

Modern neutrino observatories are deployed in the lakes, seas and glaciers of Antarctica (BNT-200+,(GVD), ANTARES (KM3NET), IceCube) and reach an effective volume of 1 cub. km. Their work is based on the detection of Cherenkov radiation that occurs when relativistic charged particles pass through the water of a detector.

Although the detectors are built to register neutrinos, they have special triggers for registration of the muon component, and the total exposure time is several years. The combination of these factors provides a unique opportunity to measure the spectrum of cascade showers and to obtain an estimate of the parameters of the spectrum of muons at very high energies.

Conclusion

One of the best ways for investigations of VHE muon spectrum is measuring the spectrum of stochastic energy losses (cascades).

Gigaton Cherenkov detectors allow to measure the cascade spectrum in the energy region of tens TeV – one PeV where manifestation of prompt muons is predicted.

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Energy losses connected with various types of interaction of muons in matter:

$$-\frac{dE}{dx} = a + bE \quad a,b \approx Const$$

$$\frac{dN}{dE}(E,\theta,z) = A\cdot\exp\left(-\frac{\gamma b_{eff} z}{\cos\theta}\right)\cdot\left\{E + \frac{a}{b'_{eff}}\left[1-\exp\left(-\frac{b'_{eff} z}{\cos\theta}\right)\right]\right\}^{-(\gamma+1)}\cdot f(\theta)$$

For muons with energies more than 100 TeV we get the coefficients:

$$a_{sum} = 2.5\frac{MeV\cdot cm^2}{g} \qquad b_{eff} = \kappa b_{sum} = 2.92\cdot 10^{-6}\frac{cm^2}{g} \qquad \kappa = \frac{\int_0^1 \sigma_{sum}(v)\frac{1-(1-v)^{\gamma}}{\gamma}dv}{\int_0^1 \sigma_{sum}(v)v\,dv}$$

$$b_{sum} = 3.5\cdot 10^{-6}\frac{cm^2}{g} \qquad b'_{eff} = b_{sum}\frac{\gamma\kappa - 1}{\gamma - 1} = 2.58\cdot 10^{-6}\frac{cm^2}{g}$$

Coefficients b_{eff} and b'_{eff} are connected with fluctuations of generation of muon spectrum at great depths

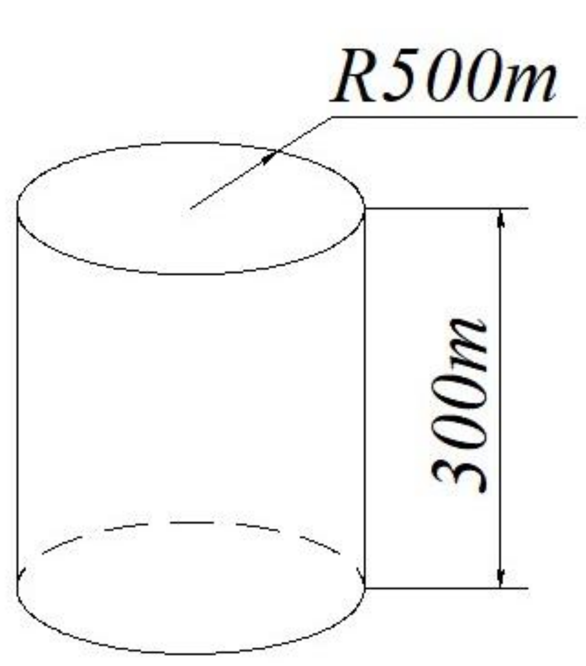
We can get the normalization constant A and $f(\theta)$ by using Gaisser's formula for the spectrum on the Earth's surface:

$$z = 0:$$

$$\frac{dN}{dE}(E,\theta) = 0.14E^{-\gamma}\cdot\left\{\frac{1}{1+\frac{1.1E\cos\theta}{115GeV}} + \frac{0.054}{1+\frac{1.1E\cos\theta}{850GeV}}\right\} \approx 20.48E^{-(\gamma+1)}\cdot\frac{1}{\cos\theta}$$

$$A = 20.48\frac{1}{s\cdot cm^2\cdot sr} \qquad f(\theta) = \frac{1}{\cos\theta}$$

Let's consider a cylindrical detector with parameters h_0 is the depth of the top of the cylinder, H is its height, R is its radius.



$$\frac{dN}{d\varepsilon d\Omega}(\varepsilon,\theta) = \int dm \int dE\sigma_{sum}(E,\varepsilon)\frac{dN}{dE}(E,\theta,z)$$

$$\rho = 0.92\frac{g}{cm^3} \qquad h_0 = 2100m, H = 300m, R = 500m$$

$$dm = \rho\pi R^2 dz$$

$$\frac{dN}{d\varepsilon d\Omega}(\varepsilon,\theta) = \rho\pi R^2\int_{h_0}^{h_0+H}dz\int_{\varepsilon}^{\infty}dE\sigma_{sum}(E,\varepsilon)\frac{dN}{dE}(E,\theta,z)$$

$$\sigma(E,\varepsilon): \sigma_{sum} = \sigma_{brem} + \sigma_{nucl} + \sigma_{pair}$$