Neutrinos from decays of stopped atmospheric muons in the Earth

Wan-lei Guo, Institute of High Energy Physics, Beijing, China

Abstract

We explore the neutrinos from decays of stopped atmospheric muons $\mu^\pm$ in the Earth. In terms of the atmospheric muon flux at the sea-level and the average muon range, we derive the depth distribution of stopped muons in the Earth. The stopped μ^- can be captured by different nuclei in the rock. Based on the mean-life of captured μ^- and the average muonic capture probabilities of different elements, we find that about 60% stopped μ^- can decay and produce the low energy neutrinos (< 53 MeV). Then we calculate the ν_e, $\bar{\nu}_e$, ν_μ and $\bar{\nu}_\mu$ fluxes from all stopped μ^+ and μ^- in the Earth, which have about 10%, 6%, 3% and 7% of the corresponding atmospheric neutrino fluxes for 1km detector depth. The new neutrino source is very helpful for us to investigate the diffuse supernova neutrinos and some related topics.

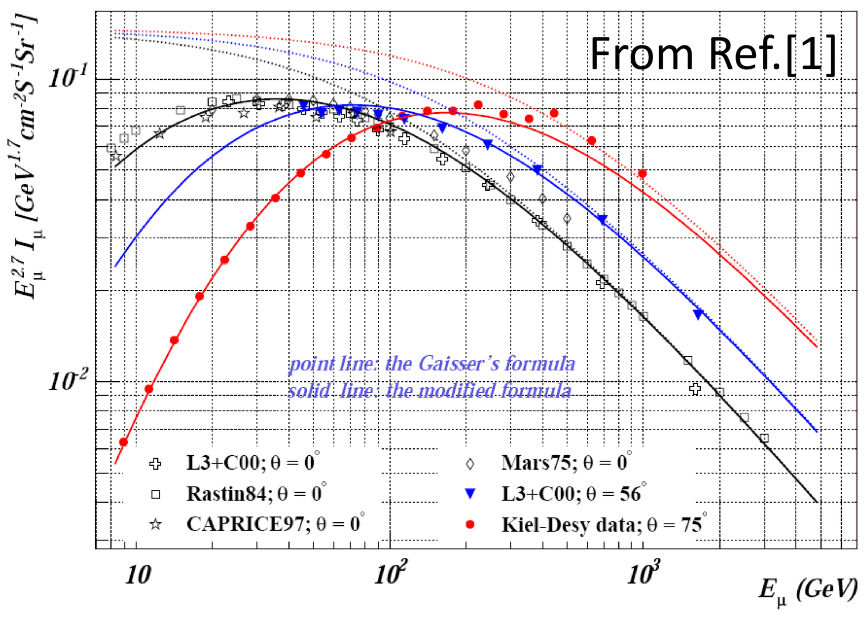
Atmospheric muon flux at the sea-level

Modified Gaisser formula [1] (> 1 GeV):

$$\frac{dI_\mu}{dE_\mu} = 0.14\left[\frac{E_\mu}{GeV}\left(1+\frac{3.64GeV}{E_\mu(\cos\theta^*)^{1.29}}\right)\right]^{-2.7} \times \left[\frac{1}{1+\frac{1.1E_\mu\cos\theta^*}{115GeV}} + \frac{0.054}{1+\frac{1.1E_\mu\cos\theta^*}{850GeV}}\right]$$

$$\cos\theta^* = \sqrt{\frac{(\cos\theta)^2+P_1^2+P_2(\cos\theta)^{P_3}+P_4(\cos\theta)^{P_5}}{1+P_1^2+P_2+P_4}}$$

P_1	P_2	P_3	P_4	P_5
0.102573	-0.068287	0.958633	0.0407253	0.817285



Total muon flux [2] → 0.0067 cm^{-2} s^{-1} (< 1 GeV) :

$$J_1 = \int I_\mu(\theta)\cos\theta\, d\omega \approx 0.0167\ \text{cm}^{-2}\ \text{s}^{-1} = (0.01 + 0.0067)\ \text{cm}^{-2}\ \text{s}^{-1}$$

Muon charge ratio [3]:

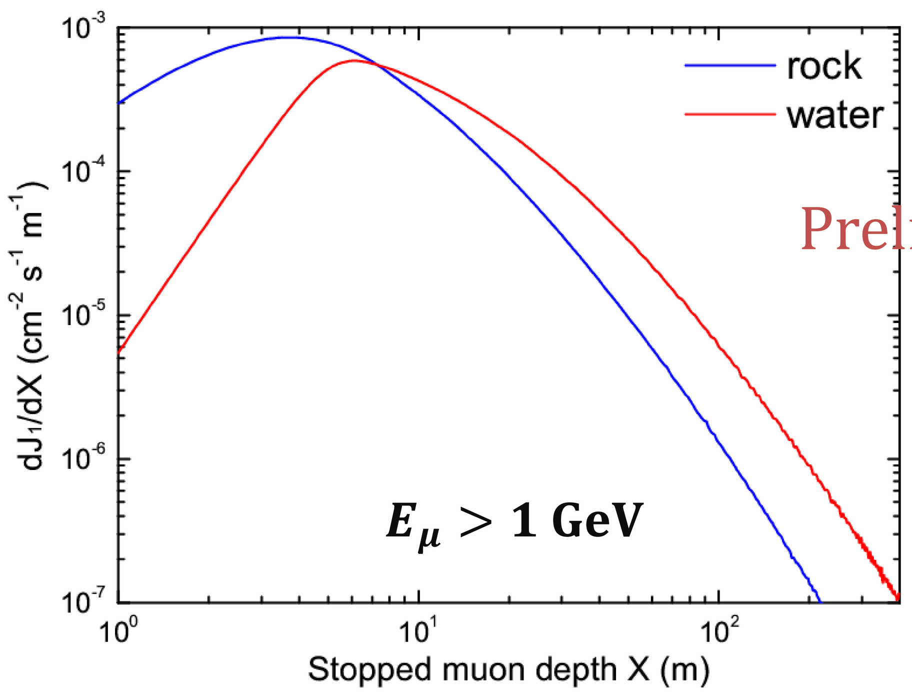
$\mu^+/\mu^- \approx 1.25$, energy dependent

Stopped muon depth distribution

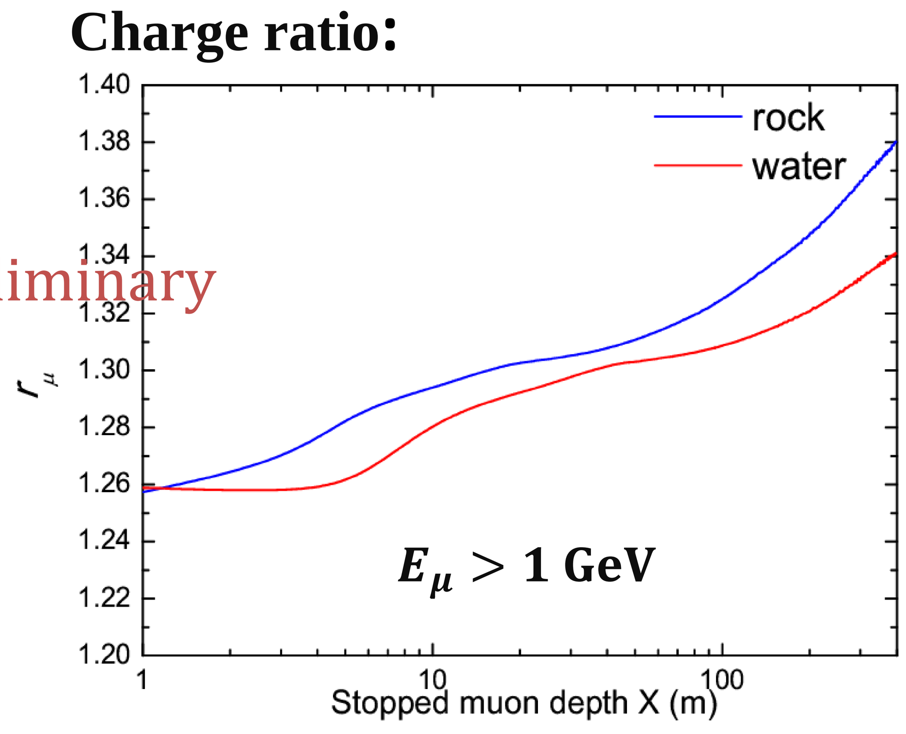
Muon energy loss: $-\frac{dE_\mu}{dL} = a + bE_\mu$ → muon range → muon depth X

http://pdg.lbl.gov/2017/AtomicNuclearProperties/

Flux distribution:



Charge ratio:



μ^- capture and decay

μ^- stops in a single element material:

1. Atomic capture → muonic atom
2. Muonic cascade → Auger e^- and X-rays
3. Nuclear capture or decay

- $\mu^- + {}^{16}O \to {}^{16}N^* + \nu_\mu$
- $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$

Neutrino energy spectrums:

$$f_{\bar{\nu}_\mu} = \frac{64}{m_\mu}\left[\left(\frac{E_\nu}{m_\mu}\right)^2\left(\frac{3}{4} - \frac{E_\nu}{m_\mu}\right)\right]$$

$$f_{\nu_e} = \frac{192}{m_\mu}\left[\left(\frac{E_\nu}{m_\mu}\right)^2\left(\frac{1}{2} - \frac{E_\nu}{m_\mu}\right)\right]$$

μ^- stops in a compound material:

We should consider muonic per atom Coulomb capture ratios for different elements. Egidy and Hartmann [4] find a semi-empirical approach and simply assessed the capture probability P(Z) for an element, normalized to 1 for oxygen.

Total nuclear capture rates:

$$\Lambda_{\text{total}} = \Lambda_{\text{capture}} + Q\Lambda_{\text{decay}}$$

$$\Lambda_{\text{total}} = \frac{1}{\tau_{\mu^-}},\quad \Lambda_{\text{decay}} = \frac{1}{\tau_{\mu^+}}$$

$\tau_{\mu^+} = 2196.98$ ns; Q: Huff factor;

→Decay ratio $D_{\mu^-} = \frac{\Lambda_{\text{decay}}}{\Lambda_{\text{total}}} = Q\frac{\tau_{\mu^-}}{\tau_{\mu^+}}$

μ^- stops in the rock:

Elements	Mass (%)	Number (%)	P(Z)	Muonic atom (%)	τ_{μ^-} (ns)	Huff factor	Decay ratio (%)
O	47.51	62.14	1.00	60.26	1795.4	0.998	81.56
Si	31.13	23.89	0.84	19.46	756	0.992	34.14
Al	8.15	3.91	0.76	2.88	864	0.993	39.05
Fe	3.92	2.27	3.28	7.21	206	0.975	9.14
Ca	2.57	2.07	1.90	3.81	332.7	0.985	14.92
Na	2.43	2.27	1.00	2.21	1204	0.996	54.58
K	2.32	1.28	1.54	1.91	435	0.987	19.54
Mg	1.50	1.99	0.93	1.79	1067.2	0.995	48.33
Ti	0.38	0.17	2.66	0.45	329.3	0.981	14.70
P	0.07	0.02	1.04	0.02	611.2	0.991	27.57

$D_{\mu^-} = 60.65\%$

1. Mass (%) comes from the upper continental crust [5]
2. P(z) denotes average capture probability relative to O16 [4]
3. Water is a O16 target since $\mu^- p$ easily penetrate nearby atoms

Neutrinos from stopped muon decay

Neutrino flux:

$$\frac{d\phi_{\nu_i}}{dE_{\nu_i}} = f_{\nu_i}\int \frac{dJ_1}{dX}A(X,d)\left\{\begin{array}{c}\frac{r_\mu}{1+r_\mu} * 1 \\ \frac{1}{1+r_\mu} * D_{\mu^-}\end{array}\right\} dX$$

X: stopped $\mu^\pm$ depth
d: detector depth
$r_\mu(X)$: μ^+/μ^-
D_{μ^-}: decay ratio

Geometry enhancement factor *A(X,d)*:

$$A(X,d) = \int \frac{2\pi R_\mu^2 \sin\vartheta}{4\pi R'^2} d\vartheta$$

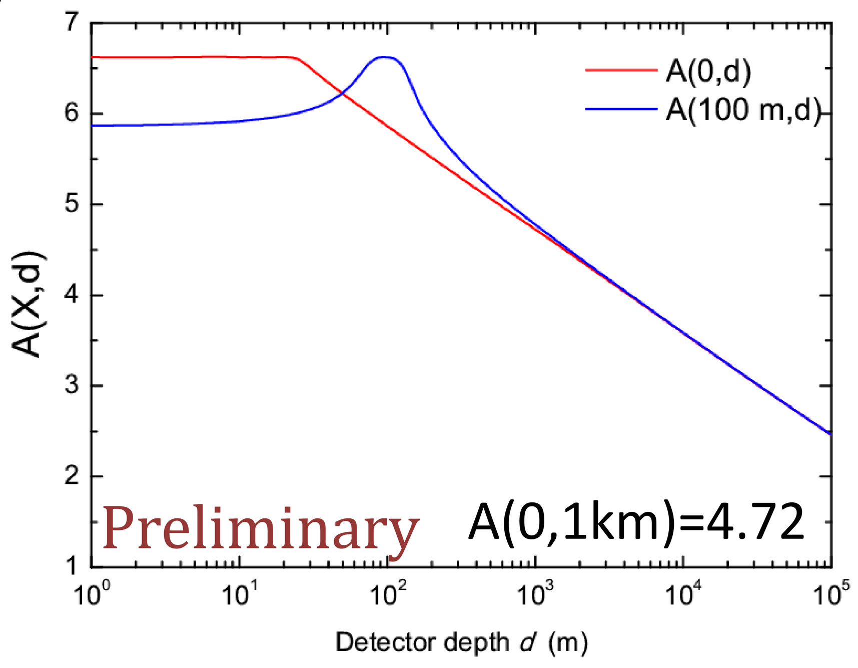
Neutrino flux from spherical distribution $\mu^\pm$ decay depends on the detector depth

$R_\mu = R - X$; $R = 6371\ km$;

R' is distance between $\mu^\pm$ and detector

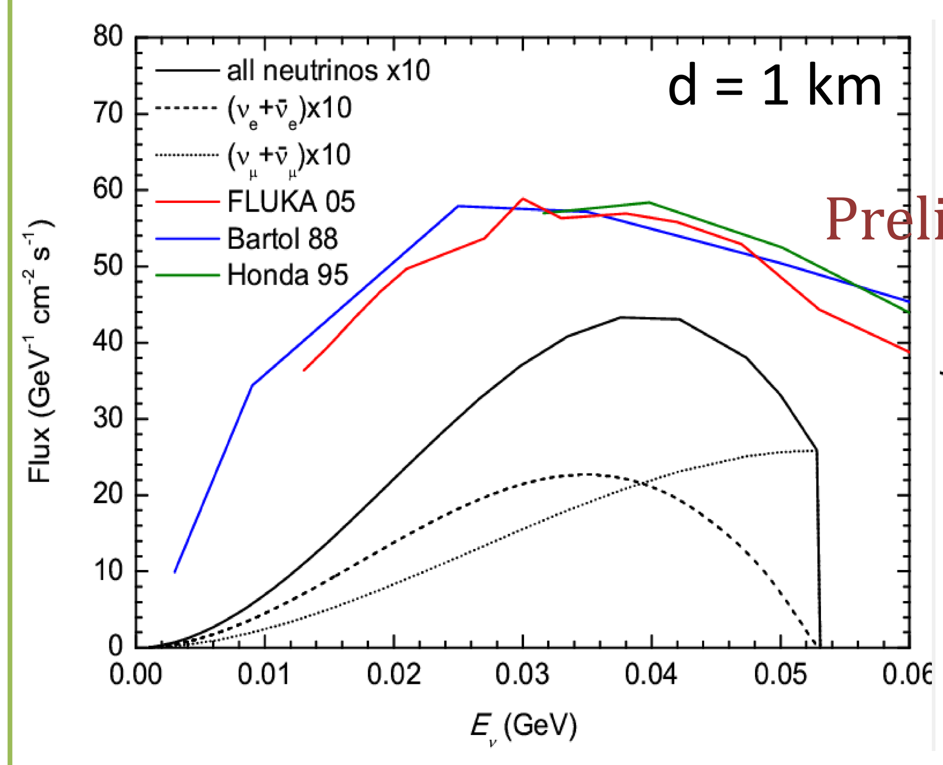
$R'^2 = R_\mu^2 + (R-d)^2 - 2R_\mu\cos\vartheta\,(R-d)$

$d = R$ (earth's core) → $A(X, 6371km) \equiv 1$

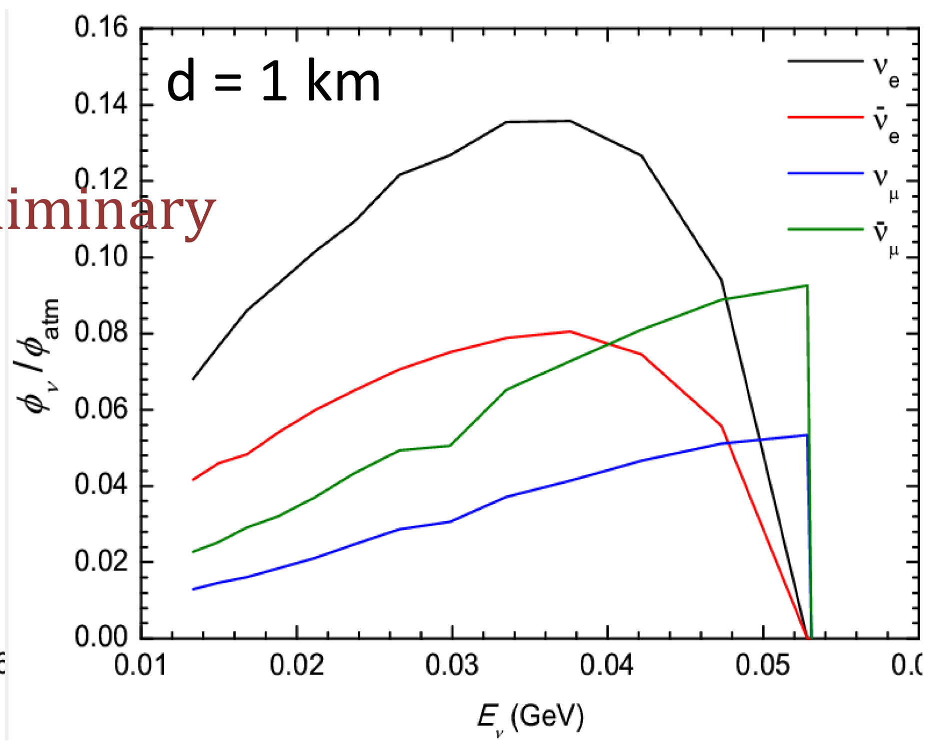


Numerical results

Neutrino fluxes:



Flux ratio (FLUKA 05):



- If d<10m, the above results will be increased by a factor 1.4
- More details on this topic please see my near future paper
- or email to guowl@ihep.ac.cn

References

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