Radiation Detector 2017/18 (SPA6309), Tutorial 2

Name:

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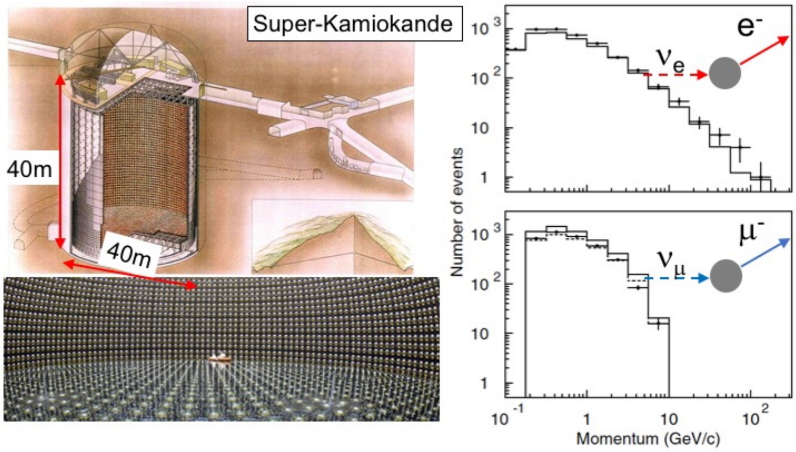


Super-Kamiokande (Super-K) is a massive neutrino detector in Japan. It is a cylindrical tank (40m height, 40m diameter) filled with water. Electron neutrinos and muon neutrinos produced at the atmosphere (atmospheric neutrinos) comes into the tank and interact with neutrons to create electrons and muons. Charged particles in the water will generate Cherenkov radiation, and by observing that we know there is a neutrino interaction. The data shows measured distributions of the momentum of electrons and muons from neutrino interactions.

problem

[1] There is no data for muons at the lowest energy bin, but lots of electrons. Why is that? Can you design an "upgrade" of the Super-K detector which is capable to measure low energy muons?

[2] The energy for muons above 10 GeV/c cannot be determined in Super-K, but for electrons above 10 GeV/c the energy can be determined. Why is this? Can you design an "upgrade" of the Super-K detector which is capable to measure muon energy above 10 GeV/c?

[3] Estimate the rate of cosmic rays in the detector, if the detector is located on the surface of the Earth? Then how deep the detector should be located, if you want to avoid the cosmic rays in the detector? Use $2.7g/cm^3$ as the Earth crust (surface layer) density.

[4] Atmospheric muon neutrinos come from all directions (isotropic) with the flux of $4\pi \times 10^{-2}/cm^2/sec$ at 1 GeV, but we are most interested in muon neutrinos coming from the bottom of the detector which creates up-going muons because it's very easy to distinguish from cosmic ray muons (they are only down-going). Using the cross-section of CC interaction of muon neutrinos with neutrons is $1 \times 10^{-38}cm^2$ at 1 GeV, estimate how many up-going muons are created in the tank per day?

Hint: atmospheric neutrinos come to the Super-K detector from every direction, but the solid angle of them to make up-going muon is roughly 0.66 Sr.

solution

[1] The Cherenkov threshold (momentum) for electron and muon are,

In [5]:
```
import numpy as np
beta=1.0/1.33
gamma=1.0/np.sqrt(1-beta**2)
print "T(e)=",0.511*beta*gamma,"MeV/c"
print "T(mu)=",106.6*beta*gamma,"MeV/c"
```

```
T(e)= 0.582754948011 MeV/c
T(mu)= 121.568840427 MeV/c
```

Therefore not many muons exceed the threshold at the first bin. On the other hand, all electrons exceed the Cherenkov threshold.

To measure low energy muons

1. replace water with liquid with small refraction index (=smaller Cherenkov threshold)
2. measure muon energy not by Cherenkov radiation, but by other processes (scintillation light?)

[2] To measure the energy of MIP muons created by neutrino interaction in the tank, you need to stop muons completely within the tank. The diagonal length of the tank is

In [14]:
```
print 40*np.sqrt(2),"m"
```

```
56.5685424949 m
```

By using water density (1g/cm^3) and MIP energy loss (2 MeV/cm for 1g/cm^3), the largest energy loss by a MIP particle created in the tank is

In [2]:
```
import numpy as np
E=56.568*100*2*0.001
print E,"GeV"
```

```
11.3136 GeV
```

Thus the momentum is

In [15]:
```
M=0.1066
P=np.sqrt(E**2-M**2)
print P,"GeV/c"
```

```
11.3130977809 GeV/c
```

Therefore it's not possible to measure the energy of muons higher than ~ 11 GeV/c. Notice for relativistic particles ($T >> m$), kinetic energy and total energy and momentum are all very similar.

There are several potential upgrades of the detector to measure muons energy higher than 10 GeV/c.

1. make detector bigger,
2. replace water with some denser liquid,
3. apply a magnetic field so that you can measure energy from the curvature of tracks, not range,

Anything else?

[3] The rough estimation can be given just from "1 cosmic muon per second per 10cm^2". Apply this to the top area of Super-K,

In [1]:
```
area=3.14*2000**2
print area/10,"Hz"
```

```
1256000.0 Hz
```

Thus the cosmic ray rate in the detector is about 1MHz. Since the cosmic rays are roughly 4 GeV, to lose all energy by ionization loss, muon needs to travel a long distance in the Earth crust.

In [19]:
```
print 4000/(2*2.7),"cm"
```

```
740.740740741 cm
```

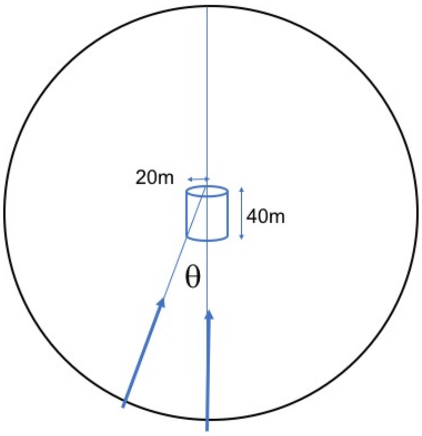
So the naive estimation says ~8m is enough depth to avoid cosmic rays. In reality, this is not correct since there are many high energy cosmic rays which penetrate deeper underground. Super-Kamiokande detector is located inside of a mountain (~1km), but it still sees many cosmic rays.

[4] The event number N is $N = \Phi \times \sigma \times T \times t$. Here 3 numbers can be obtained immediatelly.

In [22]:
```
sigma=1E-38
T=3.14*2000**2*4000*8/18*6.022E23
t=60*60*24
print "cross-section=",sigma,"cm2, target neutron number=",T,",
```

```
cross-section= 1e-38 cm2, target neutron number= 1.34464568889
e+34 , and exposure= 86400 sec
```

The tricky one is to estimate the local flux. We need to find the solid angle to estimate the number of neutrino neutrinos passing through the detector from the bottom.



In [39]:
```
costheta=40.0/np.sqrt(40.0**2+20.0**2)
print "costheta=",costheta
```

```
costheta= 0.894427191
```

since solid angle element is $sin\theta d\phi d\theta$, solid angle is
$\int_0^{2\pi}\int_0^{\theta} sin\theta d\phi d\theta = 2\pi\int_{cos\theta}^{1} dcos\theta = 2\pi(1-cos\theta)$

In [41]:
```
solidangle=2*np.pi*(1-costheta)
print solidangle,"Sr"
```

```
0.663333522347 Sr
```

Total solid angle is 4π, thus the flux is $4\pi \times 10^{-2} \times 0.66/4\pi$.

In [3]:
```
Phi=4*np.pi*1E-2*0.66/(4*np.pi)
print Phi,"cm2/sec"
```

```
0.0066 cm2/sec
```

Put everything together,

In [50]:
```
N=Phi*sigma*T*t
print N,"events per day"
```

```
0.766770757632 events per day
```

So you don't expect many events from atmospheric muon neutrinos. In reality, you have other types of interaction, and the cross section is a bit higher for higher energy, and you will get few events per day (but not 10 events).