Neutrino Physics

陆锦标 Kam-Biu Luk

Tsinghua University

and

University of California, Berkeley

and

Lawrence Berkeley National Laboratory

Lecture 6, 11 June, 2007

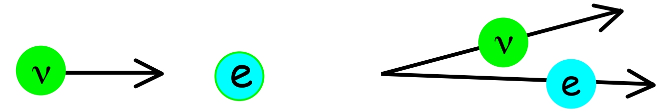
Outline

- Neutrino interactions
  - elastic scattering
  - inelastic scattering
- Background
  - cosmic ray
  - natural radiation
  - spallation neutron
- Reduction of background

ν_e Interactions

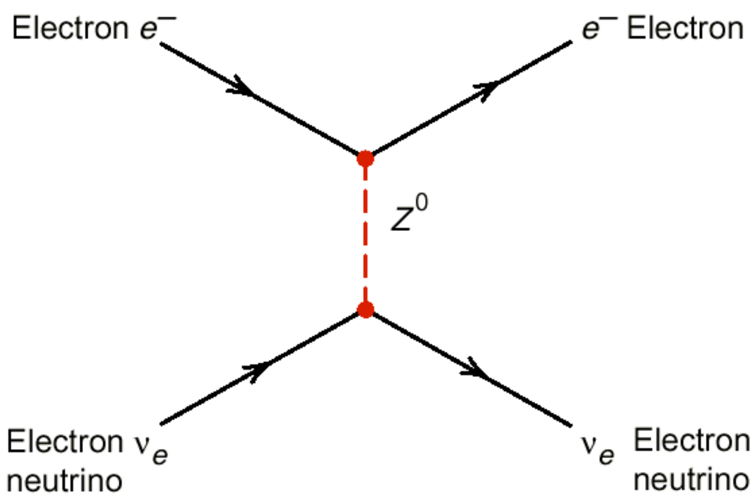
- ν_e interacts with atomic electrons: elastic scattering

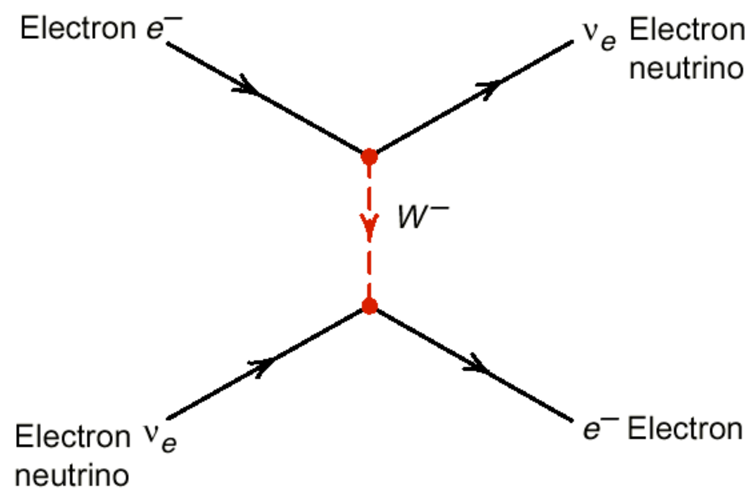
$$\nu_e + e^- \rightarrow \nu_e + e^-$$



Initial State | Final State

Initial state | Final state





$$\sigma(\nu_e e \rightarrow \nu_e e) = \frac{G_F^2 s}{\pi}\left[\left(\frac{1}{2} + \sin^2\theta_W\right)^2 + \frac{1}{3}\sin^4\theta_W\right]$$

$$\approx 9.5 \times 10^{-45}\left(\frac{E_\nu}{1MeV}\right) cm^2$$

$\sin^2\theta_W = 0.23$

G_F = Fermi constant

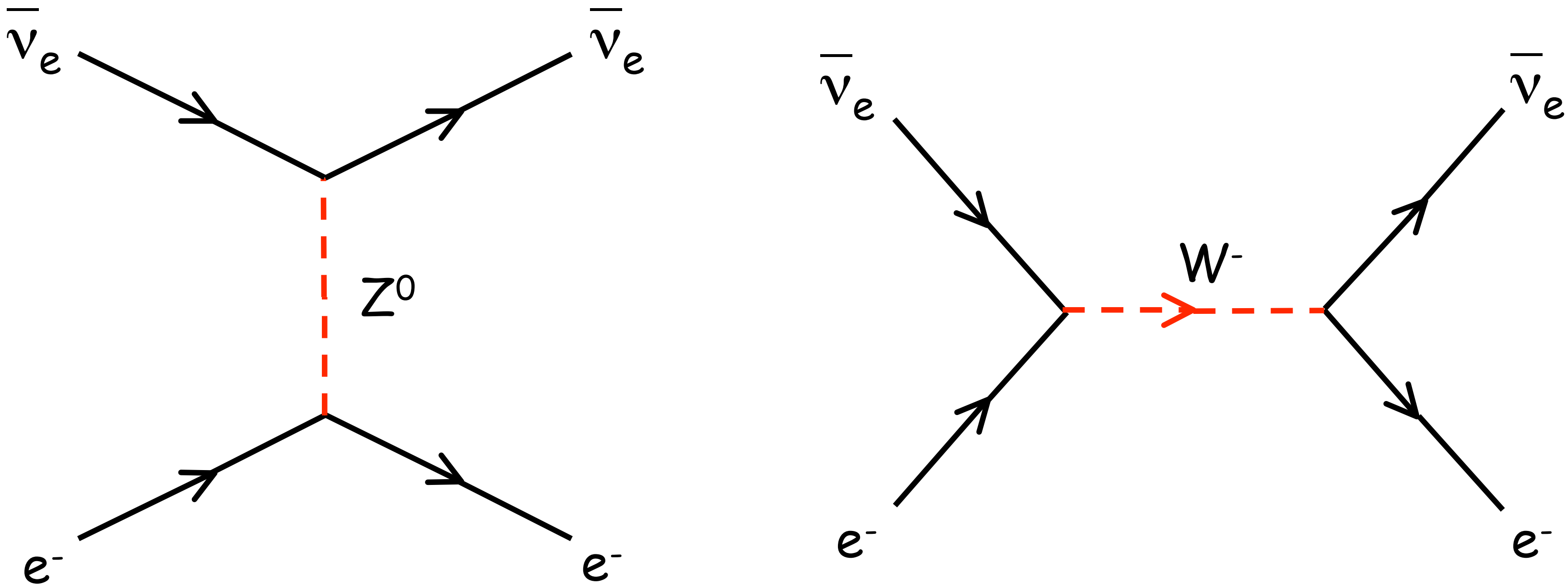
$=1.167\times10^{-5}\ GeV^{-2}$

It can take place at any energy.

$\bar{\nu}_e$ Interactions

- $\bar{\nu}_e$ interactions with atomic electrons: elastic scattering

$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$$



$$\sigma(\bar{\nu}_e e \rightarrow \bar{\nu}_e e) = \frac{G_F^2 s}{\pi}\left[\frac{1}{3}\left(\frac{1}{2} + \sin^2\theta_W\right)^2 + \sin^4\theta_W\right]$$

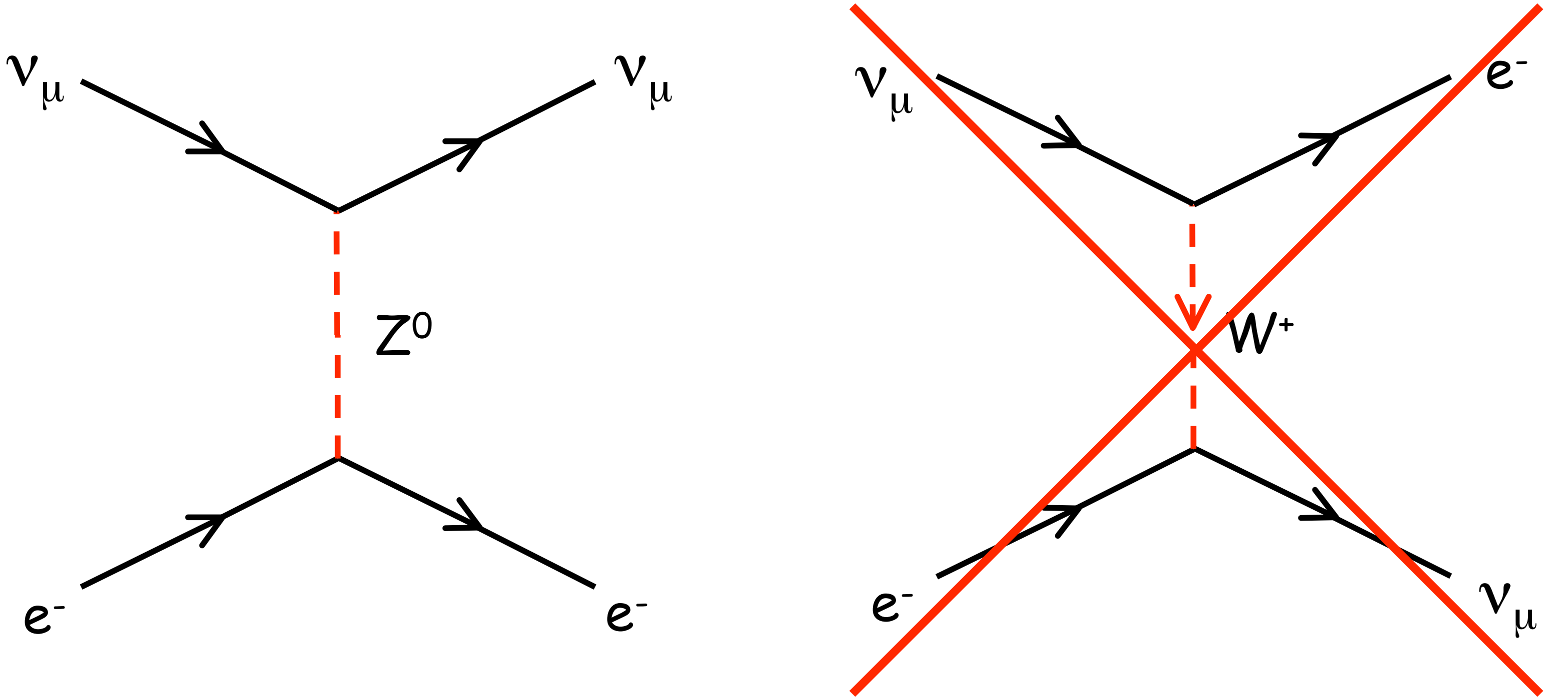
$$\approx 4.0 \times 10^{-45}\left(\frac{E_\nu}{1MeV}\right)\ cm^2$$

It can also take place at any energy.

ν_μ Interactions

- ν_μ interactions with atomic electrons: elastic scattering

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$



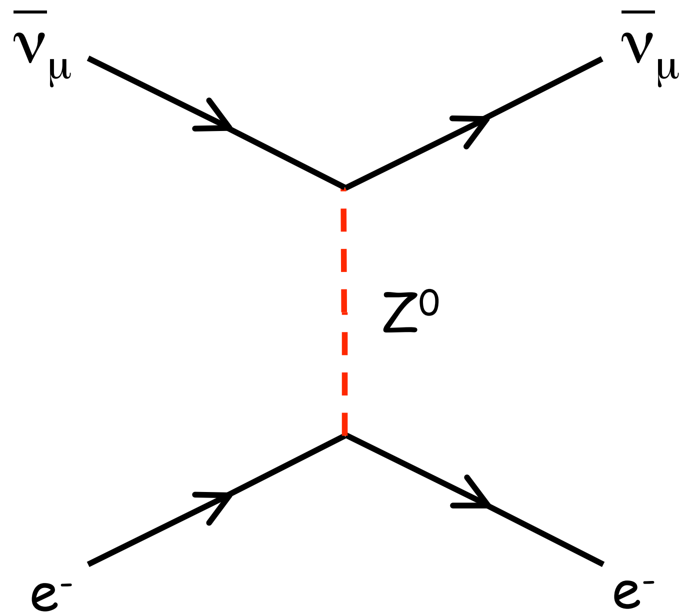
$$\sigma(\nu_\mu e \rightarrow \nu_\mu e) = \frac{G_F^2 s}{\pi}\left[\left(\frac{1}{2} - \sin^2\theta_W\right)^2 + \frac{1}{3}\sin^4\theta_W\right]$$

$$\approx 1.6 \times 10^{-45}\left(\frac{E_\nu}{1MeV}\right)\ cm^2$$

$\bar{\nu}_\mu$ Interactions

- $\bar{\nu}_\mu$ interactions with atomic electrons: elastic scattering

$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$$



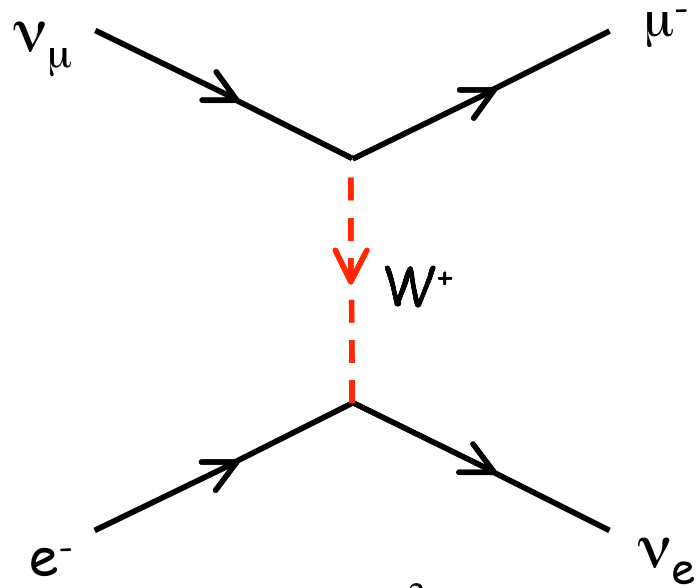
$$\sigma(\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e) = \frac{G_F^2 s}{\pi}\left[\frac{1}{3}\left(\frac{1}{2} - \sin^2\theta_W\right)^2 + \sin^4\theta_W\right]$$

$$\approx 1.3 \times 10^{-45}\left(\frac{E_\nu}{1MeV}\right)\ cm^2$$

Inelastic ν_μ Interactions

- ν_μ interactions with atomic electrons:

$$\nu_\mu + e^- \rightarrow \nu_e + \mu^-$$



$$\sigma(\nu_\mu e \rightarrow \nu_e \mu) = \frac{G_F^2}{\pi}\frac{\left(s - m_\mu^2\right)^2}{s} \quad \textit{for low energies}$$

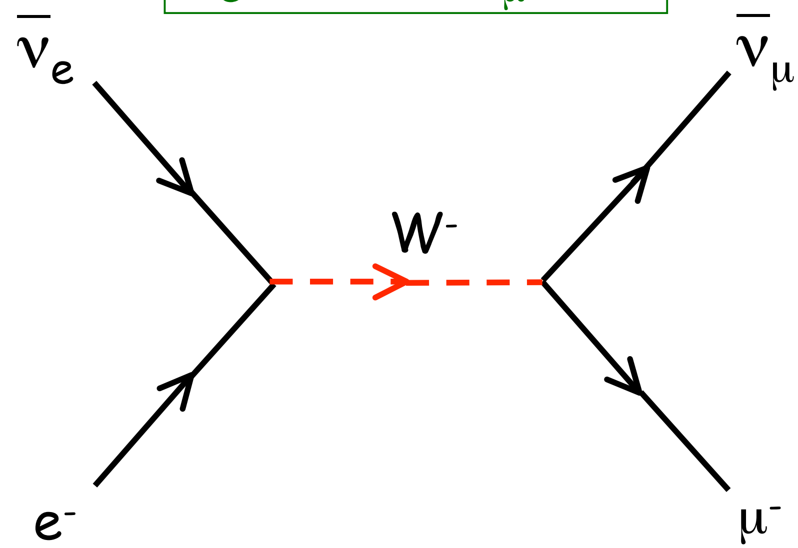
$$= \frac{G_F^2 s}{\pi} \quad \textit{for high energies}$$

$$\approx 17 \times 10^{-45}\left(\frac{E_\nu}{1MeV}\right)\ cm^2$$

Inelastic $\bar{\nu}_e$ Interactions

- $\bar{\nu}_e$ interactions with atomic electrons:

$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_\mu + \mu^-$$



$$\sigma(\nu_\mu e \rightarrow \nu_e \mu) = \frac{G_F^2}{3\pi}\frac{\left(s - m_\mu^2\right)^2}{s} \quad \textit{for low energies}$$

$$= \frac{G_F^2 s}{3\pi} \quad \textit{for high energies}$$

$$\approx 5.7 \times 10^{-45}\left(\frac{E_\nu}{1MeV}\right) cm^2$$

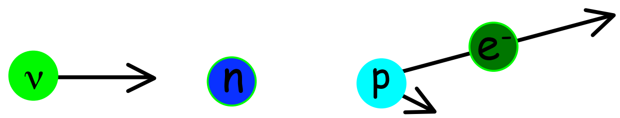
Tau Neutrino Interactions

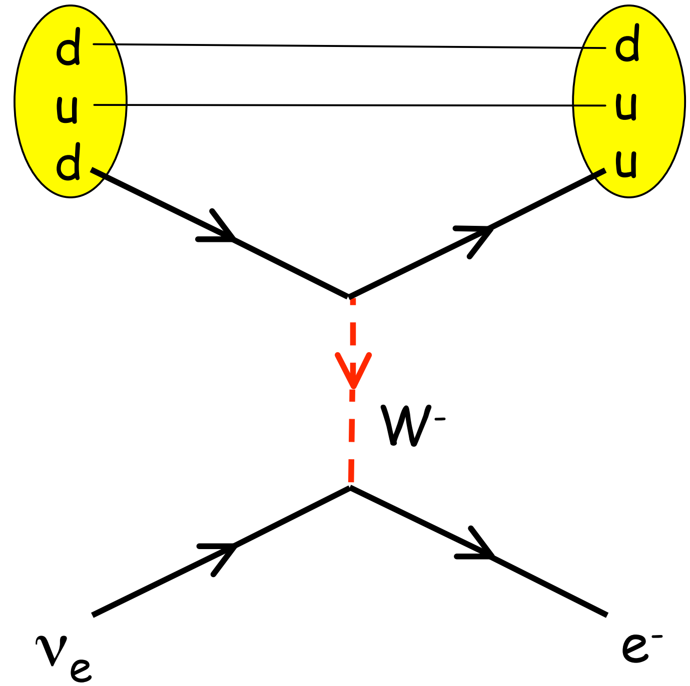
The cross sections of ν_τ and $\bar{\nu}_\tau$ with electron are identical to those of the muon neutrinos.

Neutrino-nucleon Interactions

$\nu_e + n \rightarrow e^- + p$

In the laboratory,





For less than 1 GeV,

$$\sigma(\nu_e n \rightarrow e^- + p) = \frac{G_F^2 E_\nu^2 (\hbar c)^2}{\pi}(g_V^2 + 3g_A^2)\left(1+\frac{Q}{E_\nu}\right)\sqrt{1+2\frac{Q}{E_\nu}+\frac{Q^2-m_e^2}{E_\nu^2}}$$

$$= 9.3\times 10^{-44}\left(\frac{E_\nu}{1MeV}\right)^2\left(1+\frac{Q}{E_\nu}\right)\sqrt{1+2\frac{Q}{E_\nu}+\frac{Q^2-m_e^2}{E_\nu^2}}\ cm^2$$

where g_V = 1, vector coupling constant,
g_A = 1.23, axial-vector coupling constant,
Q = m_n - m_p = 1.3 MeV

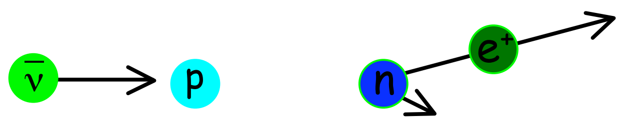
Neutral-current Interaction With Nucleon

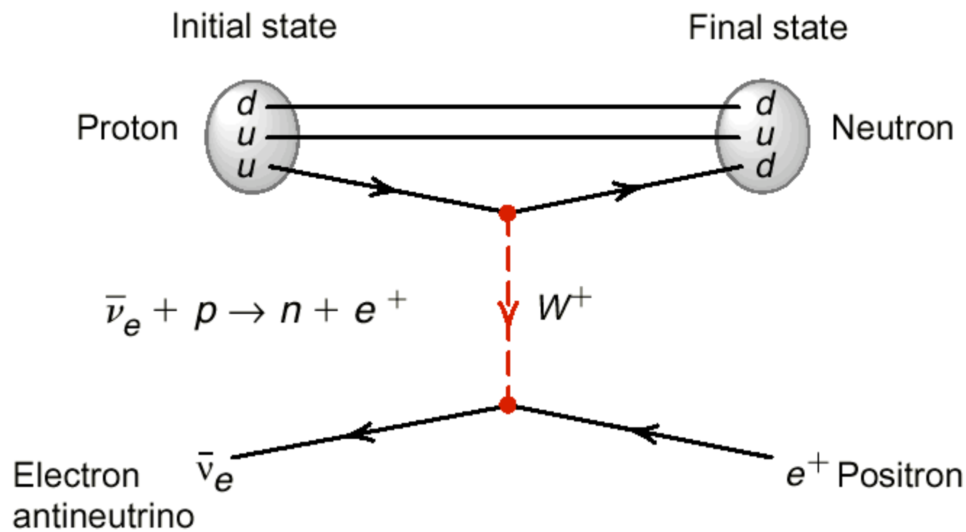
Antineutrino-nucleon Interactions

Inverse beta-decay reaction:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

In the laboratory,





For less than 1 GeV,

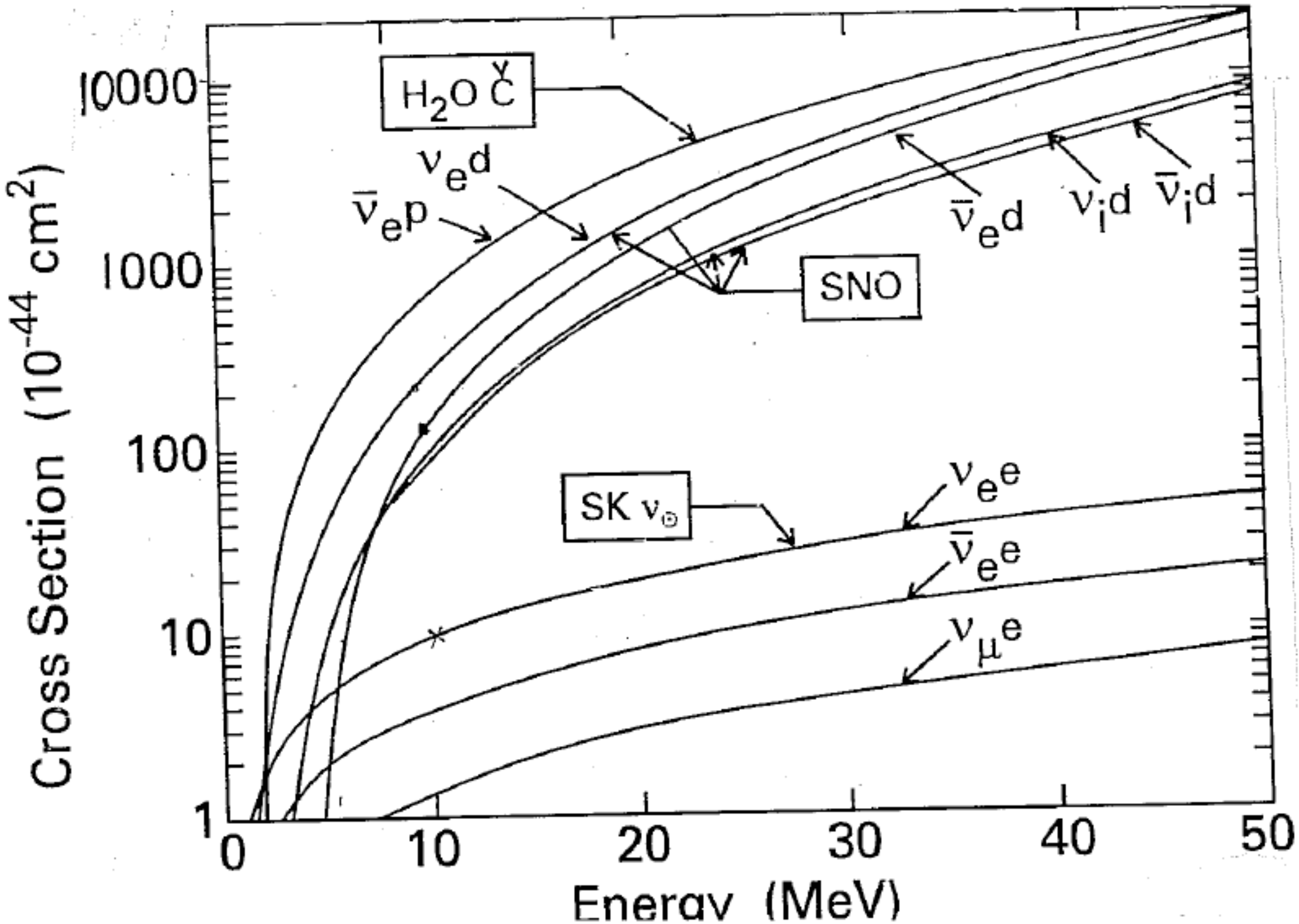
$$\sigma(\bar{\nu}_e p \rightarrow e^+ + n) = \frac{G_F^2 E_\nu^2 (\hbar c)^2}{\pi}(g_V^2 + 3g_A^2)\left(1 - \frac{Q}{E_\nu}\right)\sqrt{1 - 2\frac{Q}{E_\nu} + \frac{Q^2 - m_e^2}{E_\nu^2}}\,\theta(E_\nu - Q)$$

$$= 9.3 \times 10^{-44}\left(\frac{E_\nu}{1MeV}\right)^2\left(1 - \frac{Q}{E_\nu}\right)\sqrt{1 - 2\frac{Q}{E_\nu} + \frac{Q^2 - m_e^2}{E_\nu^2}}\,\theta(E_\nu - Q)\ \ cm^2$$

where $\theta(E_\nu - Q) = 1$, for $E_\nu > Q$ threshold function

$= 0$, for $E_\nu < Q$

Cross Sections Of Low-energy ν Scattering

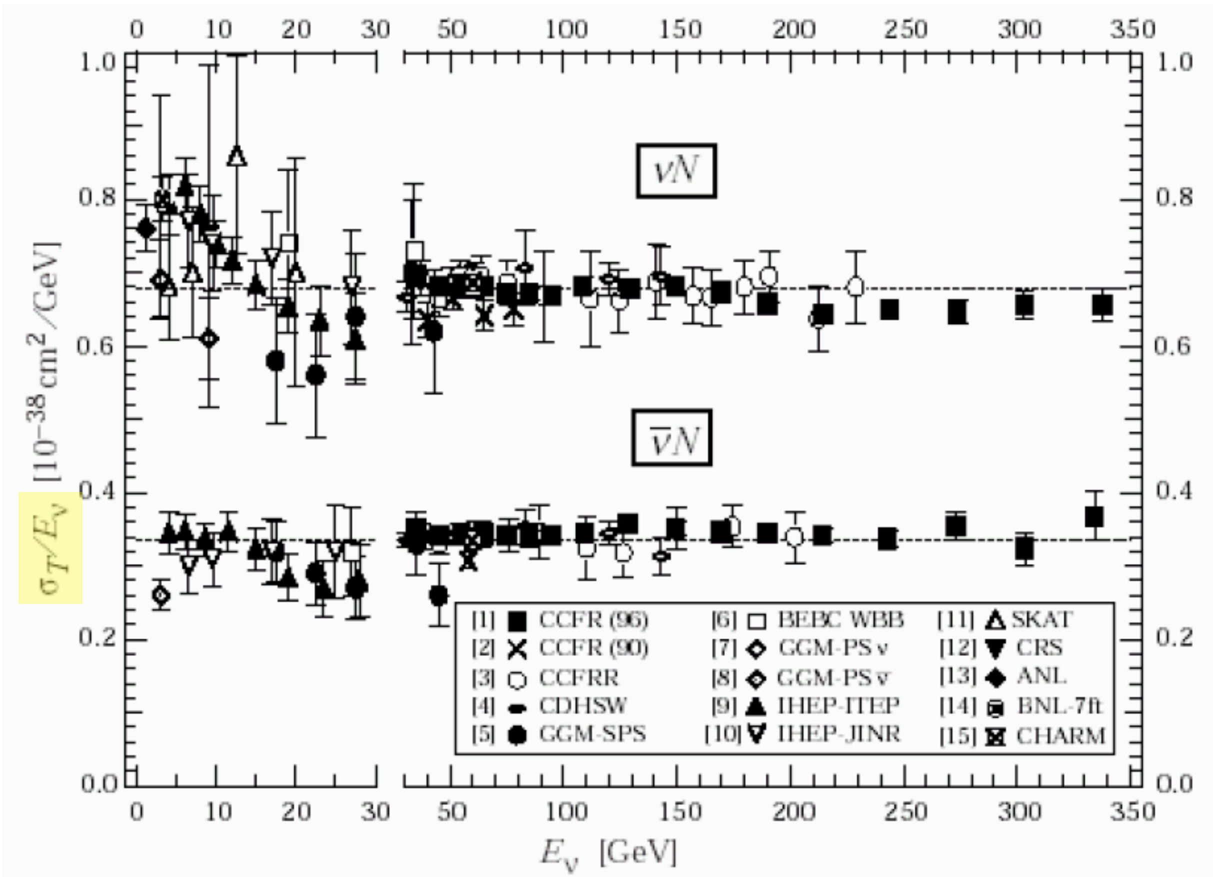


Interactions With Nucleons At High-energy

- For 50 GeV < E_ν < 350 GeV, the inelastic cross sections are:

$$\sigma(\nu_l N \to l^- + X) \approx 6.7 \times 10^{-39} \left(\frac{E_\nu}{GeV}\right)\ cm^2$$

$$\sigma(\overline{\nu}_l N \to l^+ + X) \approx 3.4 \times 10^{-39} \left(\frac{E_\nu}{GeV}\right)\ cm^2$$



How Many Neutrino Events?

For observing solar neutrino events with the electrons in the water molecule as the targets

$$N_{det} = \sigma_{\nu e} \bullet \Phi_\nu \bullet N_{tgt}$$

where $\Phi_\nu = 7 \times 10^{10}\ cm^{-2}s^{-1}$,

$\sigma_{\nu e} \sim 10^{-45}\ cm^2$

For the target, the number of electrons in 1 mole of H_2O:

$(6 \times 10^{23}$ molecules$) \times 18\ e^-/$molecule $\sim 10^{25}\ e^-$

If 1000 tonne of water is used, then the number of e^- is

$N_{tgt} = (10^3 \times 10^3 \times 10^3/18) \times 10^{25} \sim 10^{32}$

Thus, the event rate is:

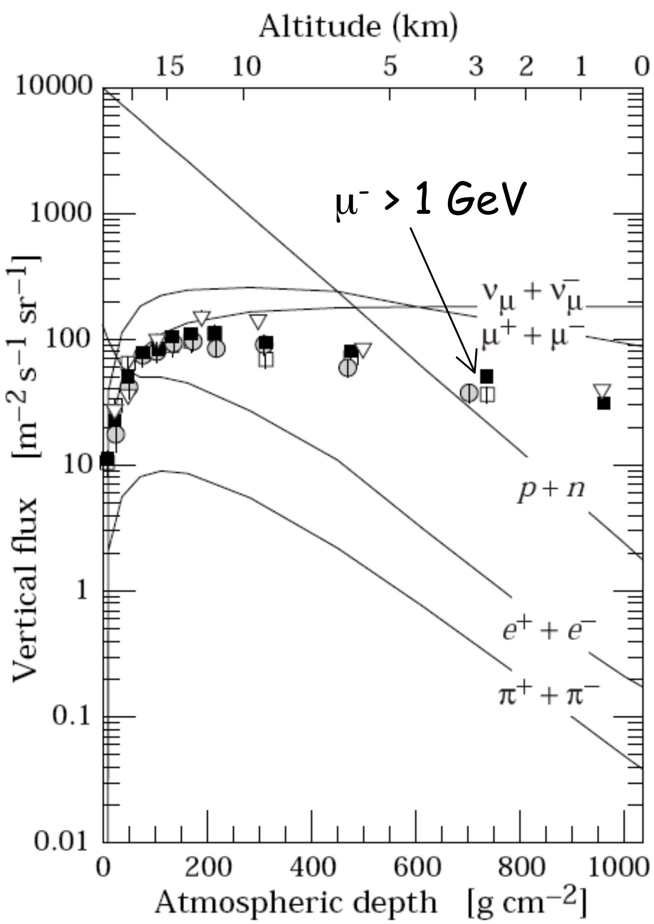
$N_{det} \sim 0.01\ s^{-1}$ or 1000 per day !!

Dark Side Of Cosmic Ray

- At sea level, the intensity of cosmic ray is ~1 $cm^{-2}min^{-1}$, and has an angular distribution given by

$$\frac{dI}{d\cos\theta} = I_0 \cos^2\theta$$

Most are muons with an average energy of ~4 GeV.



- For a 1000 t water cube at sea level, the number of muons going through is

$$\sim(10 \times 100)^2 \times 1\ \mathrm{min}^{-1} = 1.7 \times 10^4 \mathrm{s}^{-1}$$

- Muons can ionize the target along their path, and can emit Cherenkov photons:

$$\mu^- + N \rightarrow \mu^- + N^+ + e^-$$

or

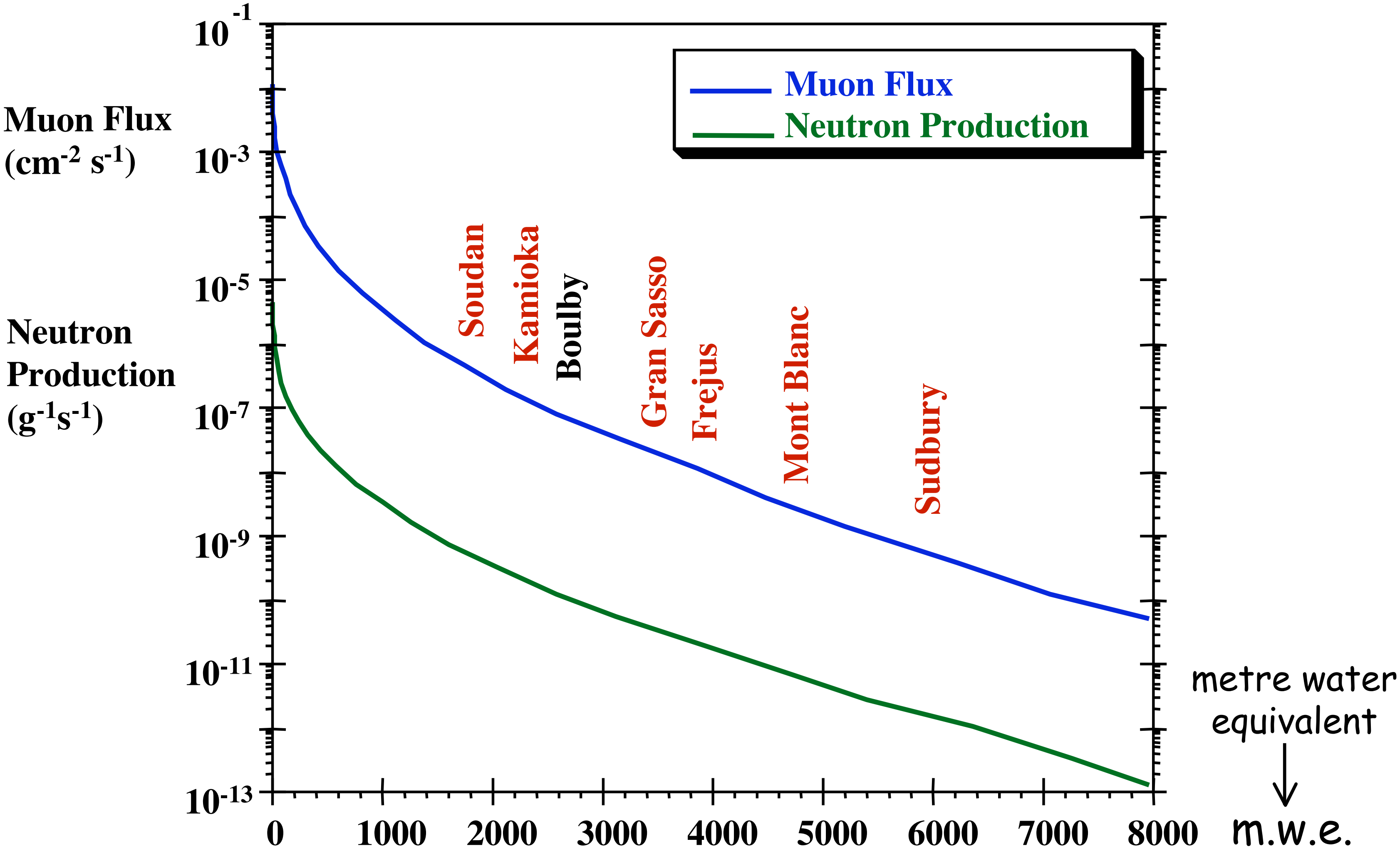
$$\mu^- + N \rightarrow n + X$$

$$\mu^- + N \rightarrow N_1 + X$$

$$\quad\quad\quad\quad \hookrightarrow N_2 + \beta + \bar{\nu}_e$$

which can mimic the neutrino reactions.

Go Underground

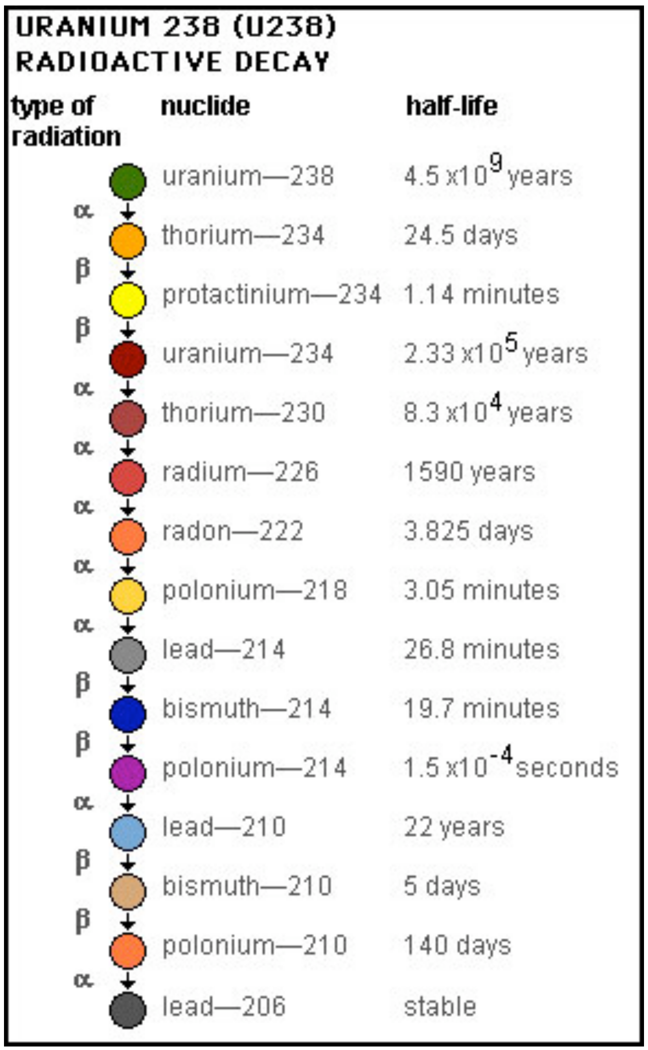


1 m of granitic rock ≈ 2.6 m of water = 2.6 m.w.e.

Muons lose energy as they go through rock. Hence they get attenuated.

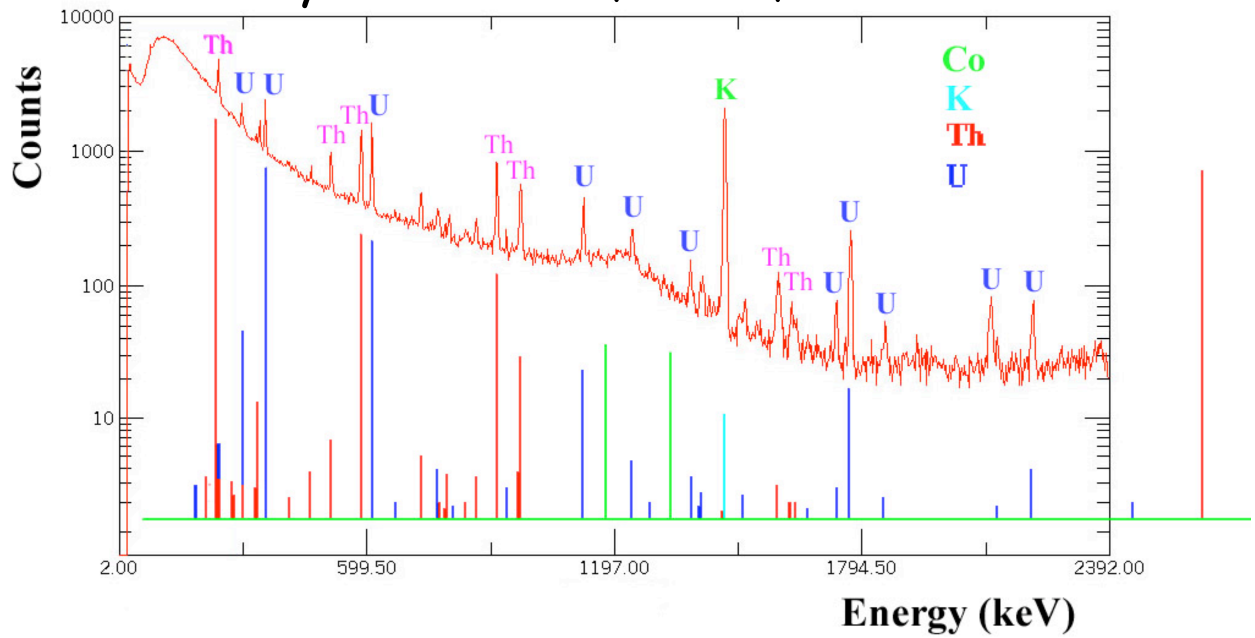
Natural Radioactivity

- The common radioactive isotopes in the environment are:



	Radioisotope impurity in rock			Depth (wme)	Cosmic ray muon flux ($cm^{-2}s^{-1}$)
	U (ppb)	K (ppm)	Th (ppb)		
Boulby	10	750	100	3300	5×10^{-8}
Gran Sasso	500	160	65	3800	1×10^{-8}
Sudbury	1200	1150	3300	6200	5×10^{-10}
Soudan	100	1200	250	2200	3×10^{-7}

Gamma rays from ^{238}U, ^{232}Th, and ^{40}K chains



More Headache Due To Radioactivity

- All materials used in the detector potentially can have natural radioactivity as well, for example, for a low background photomultiplier tube:

	^{40}K (ppm)*	^{232}TH (ppb)*	^{238}U (ppb)*
Glass	60	30	30
Ceremic	30	70	20
Metal	0	30	0
Plastic	170	30	25

* Mass of radioactive nuclide/mass of the material

- The number of gamma rays emitted is:

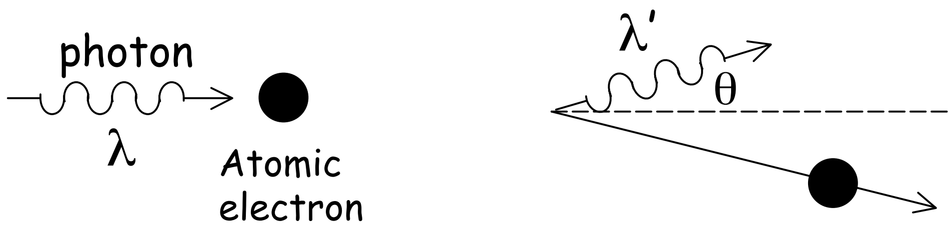
1 mg of *natural* K gives 285 γ/day with $E_\gamma > 0.1$ MeV

1 μg of Th gives 958 γ/day with $E_\gamma > 0.1$ MeV

1 μ g of U gives 2310 γ/day with $E_\gamma > 0.1$ MeV

Problem With Background Gamma Rays

- Since the energies of many of the gamma rays from natural radioactivity are more than 1 MeV, they can Compton-scatter to give energetic electrons:



- The electrons can look like those coming from ν or $\bar{\nu}$ interactions.

- A gamma ray could also combine with a low-energy n to appear as a inverse beta-decay event (gamma ray looks like e^+ as far as the detector is concerned).

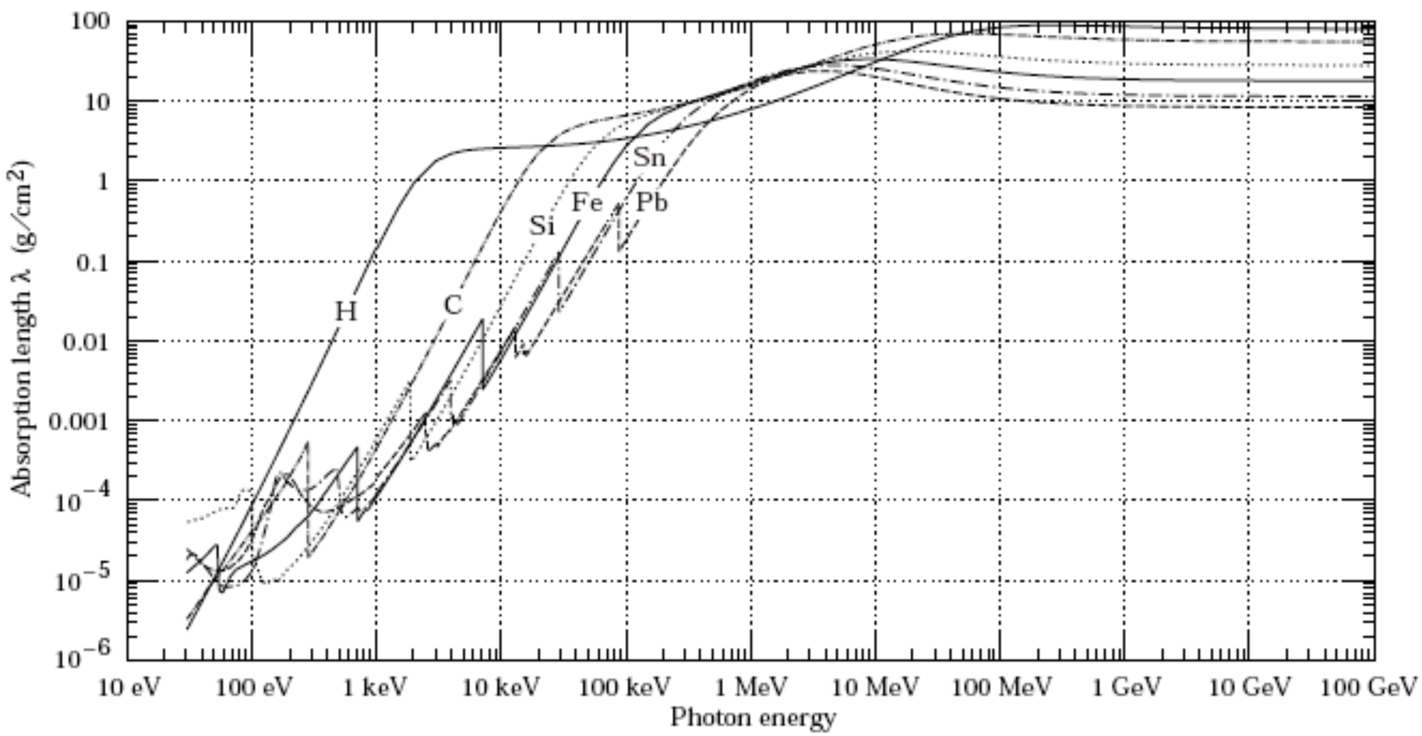
Beating Down The Background

- The intensity of radiation after passing through a thickness x of material is given by:

$$I(x) = I_0 e^{-x/\lambda}$$

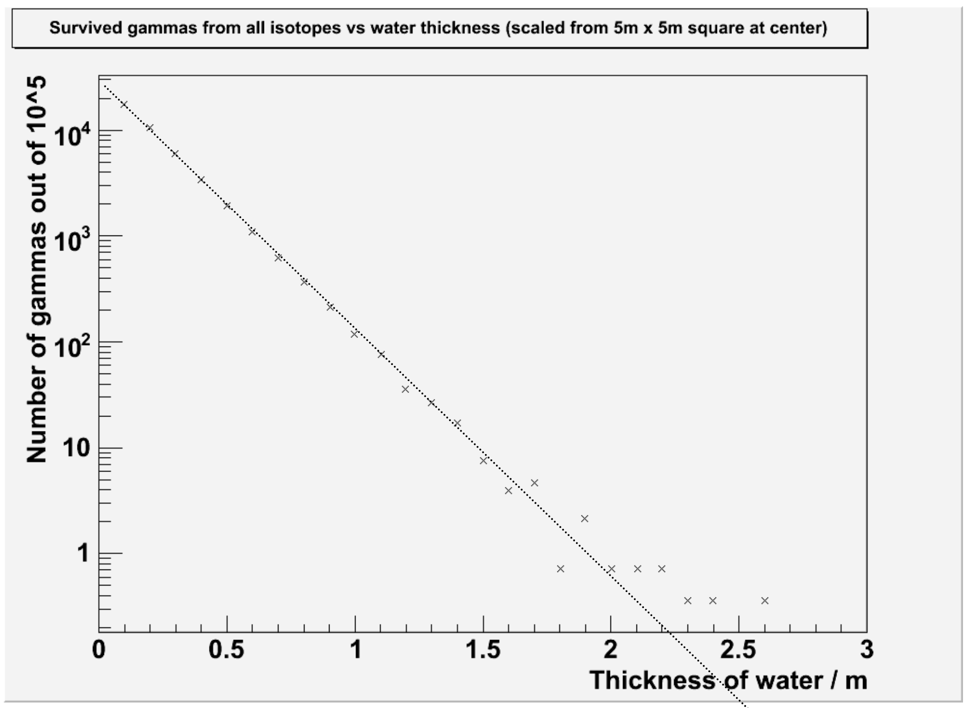
where I_0 is the initial intensity,
λ is the absorption length (for photon, this is also called radiation length)

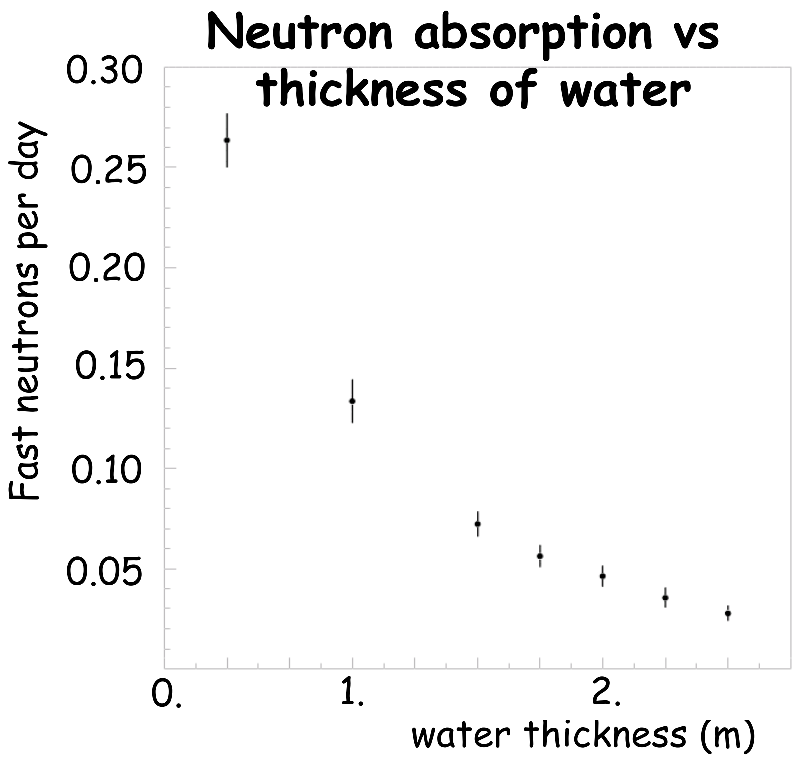
$$\lambda[cm] = \frac{\lambda\left[\frac{g}{cm^2}\right]}{\rho\left[\frac{g}{cm^3}\right]}$$



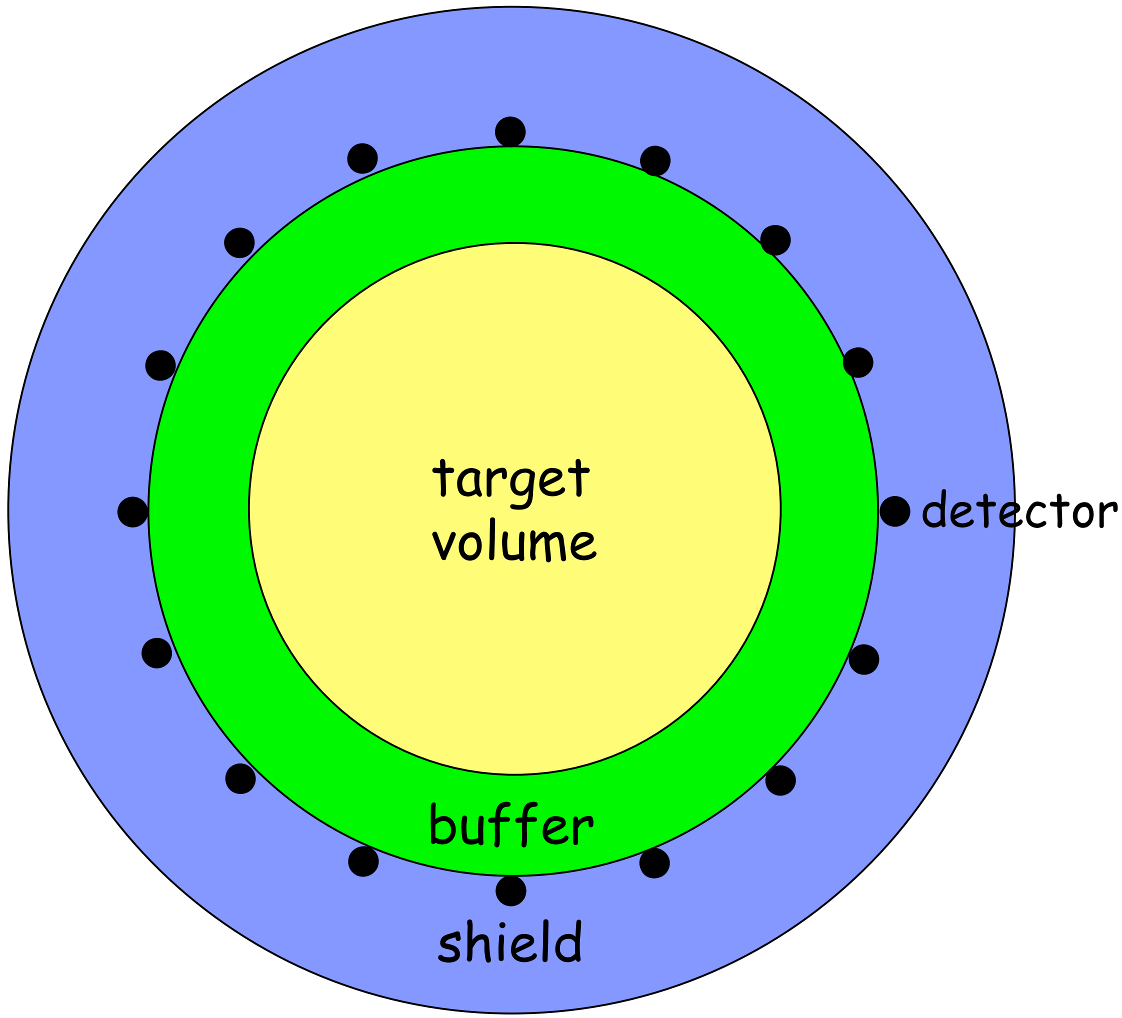
Beating Down The Background (cont.)

- The other background is the neutrons produced by muons.
- Neutrons can be attenuated with hydrogen-rich materials, e.g. water, paraffin, borated polyethylene.
- If water, cheap and easily available, is used:





Shielding Neutrino Detector For Non-accelerator Experiments



Summary

- Neutrino interactions have small cross sections at low energies, hence, low event rate.
- Cosmic ray and natural radioactivity are major background in non-accelerator neutrino experiments
- Need large, clean, and well-shielded detectors placed underground to reduce unwanted events