Basics of Analysis with Antineutrinos From Heat Producing Elements - K, U, Th in the Earth

IAP 2010, January 5 - 22

Earth, Atmospheric & Planetary Sciences
Massachusetts Institute of Technology

Session 2: January 19, 2010, 10 AM to Noon

Instructor *Dr. Ila Pillalamarri*

Course 12.091 Special Topics in Earth Sciences

Course Objectives

1) Relevance to antineutrino analysis of global concentration determination of radiogenic heat producing elements (HPE) by terrestrial heat flow studies and Bulk Silicate Earth (BSE) models, and unconventional models of the Earth's core.

2) Basic radiation characteristics of heat producing elements (HPE):

   Alpha, beta, gamma, neutrino and antineutrino radiations,

   Basics of radiation detection concepts,

   Special focus:

   Antineutrino radiation detection,

   Antineutrino radiation detection with directional sensitivity.

Course Objectives Continued

3) Relevance of existing large antineutrino detectors for probing the HPE in Earth's deep interior:

   Characteristics, research and contributions of the two existing antineutrino detectors – Sudbury Neutrino Observatory (SNO), Canada and Kamioka Liquid Scintillator Antineutrino Detector (KamLAND), Japan.

4) Proposed antineutrino detectors for probing the HPE in Earth's deep interior with directional sensitivity. Tomography of the whole Earth for the localization of the HPE in the deep interior of the Earth. Need for mobile antineutrino detectors for tomography.

5) Considerations for dedicated antineutrino detectors to probe the Earth's deep interior for the determination of concentrations of heat producing elements.

Course Schedule
January 5 – 22, 2010

Jan 05: Room 54-312

Relevance to antineutrino analysis of global concentration determination of radiogenic heat producing elements (HPE) by terrestrial heat flow studies and Bulk Silicate Earth (BSE) models, and unconventional models of the Earth's core.

Jan 19: Room 54-312

Basic radiation characteristics of heat producing elements (HPE):

Alpha, beta, gamma, neutrino and antineutrino radiations,

^{40}K decay characteristics, U and Th decay series

Basics of radiation detection concepts,

Special focus:

Antineutrino radiation detection,

Antineutrino radiation detection with directional sensitivity.

Course Schedule
January 5 – 22, 2010

Jan 20: Room 54-312

Relevance of existing large antineutrino detectors for probing the HPE in Earth's deep interior:

Characteristics, research and contributions of the two existing antineutrino detectors – Sudbury Neutrino Observatory (SNO), Canada and Kamioka Liquid Scintillator Antineutrino Detector (KamLAND), Japan.

Jan 21: Room 54-312

Proposed antineutrino detectors for probing the HPE in Earth's deep interior with directional sensitivity. Tomography of the whole Earth for the localization of the HPE in the deep interior of the Earth. Need for mobile antineutrino detectors for tomography.

Visit to Earth Atmospheric & Planetary Sciences – Radiometric/Neutron Activation Analysis Laboratory (NW13-263).

Jan 22: Room 54-312

Considerations for dedicated antineutrino detectors to probe the Earth's deep interior for the determination of concentrations of heat producing elements.

Conclusions.

Student Presentations.

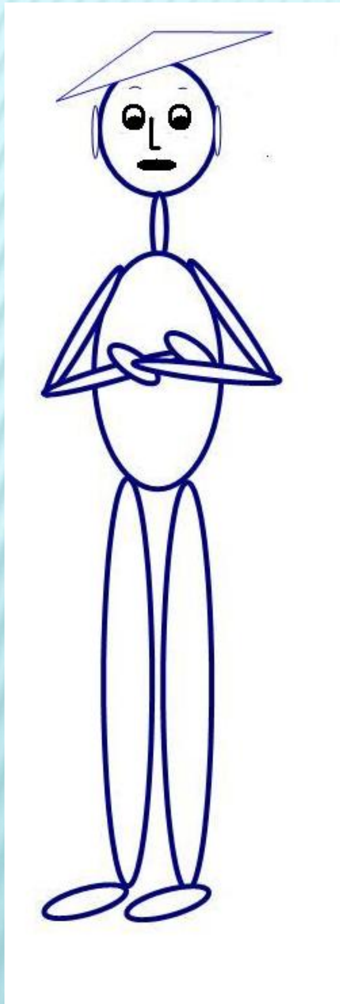
Details of course work

The course work involves the following:

1.	Class attendance and participation	25%
2.	Reading assignments	25%
3.	Homework assignments	15%
4.	Student report	15%
5.	Student presentation	15%

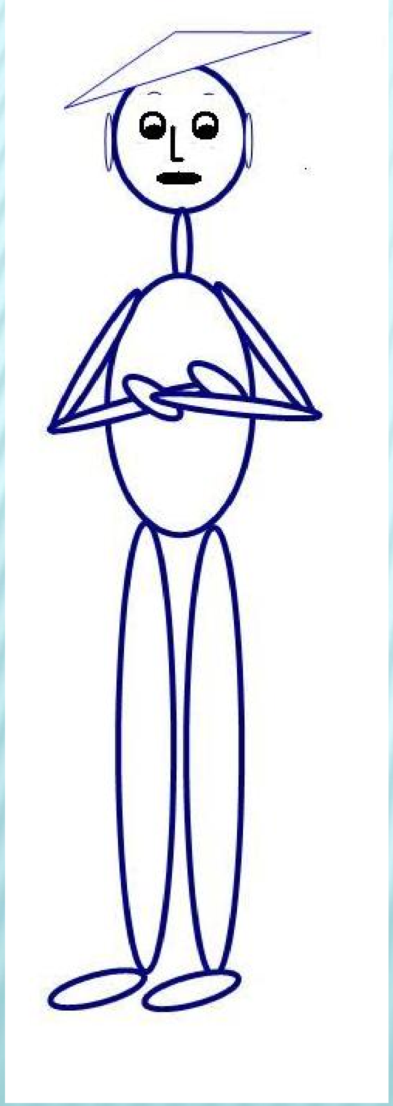
Required percentage to pass this course is 95%.

Course Overview



- Basics of
  - Analysis with
    - Antineutrinos from
      - Heat Producing Elements K, U, Th
        - In the Earth

Session 2 Objectives
January 19, 2010



By the end of this session we will learn about

- Basic radiation characteristics of heat producing elements (HPE):
  - Alpha, beta, gamma, neutrino and antineutrino radiations,
  - U and Th decay series,
  - ^{40}K decay scheme.
- Basics of radiation detection concepts, Special focus:
  - Antineutrino radiation detection,
  - Antineutrino radiation detection with directional sensitivity.

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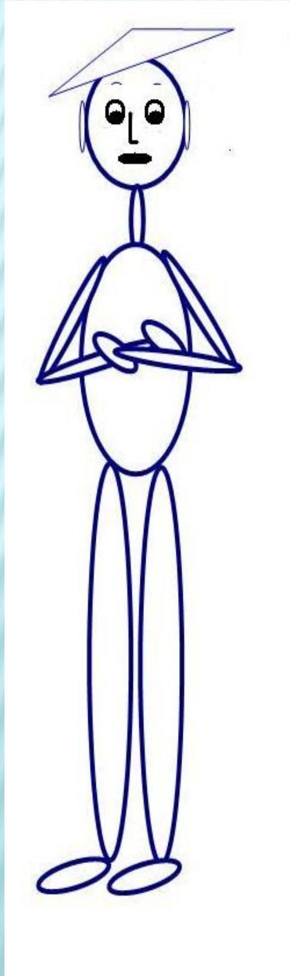
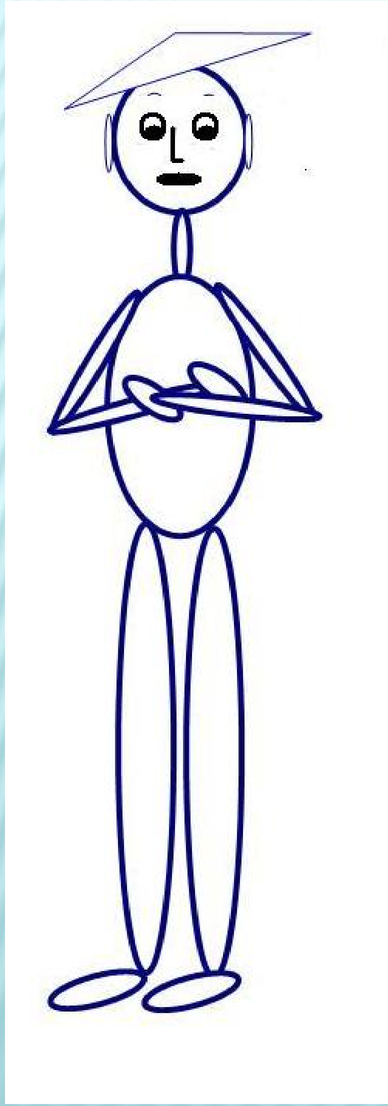


Basic Radiation characteristics of heat producing elements (HPE) :

Alpha decay, beta decay, gamma decay, Neutrino & antineutrino radiation of K, Antineutrino radiation of U, Th.

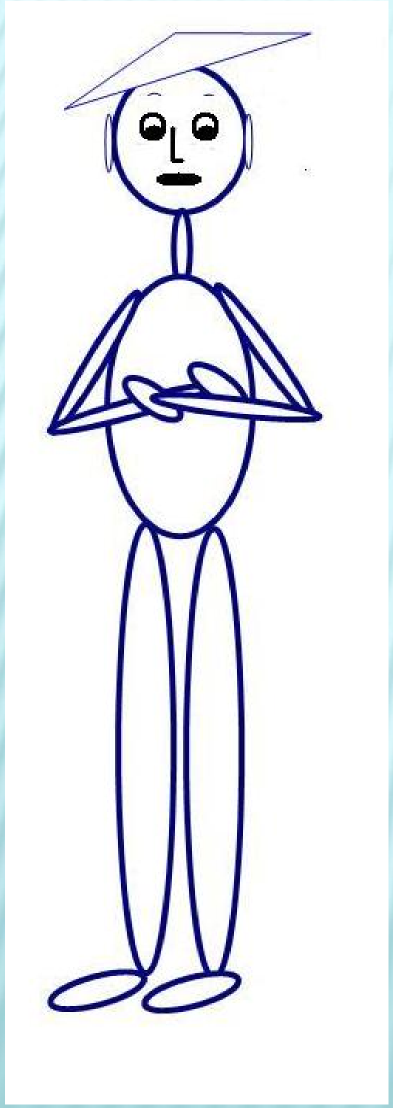
Radiation Characteristics of Heat Producing Elements – K, U, Th



The elements that contribute predominantly to terrestrial heat are K, U and Th.

- **What radioactive isotopes of these elements are of interest?**
- **What is their isotopic abundance?**
- **Why do we have to know the isotopic abundance?**
- **K, U, Th radioactive instability: Alpha decay, beta decay, gamma decay**

Radiation Characteristics of Heat Producing Elements – K, U, Th continued



- What is meant by positive and negative beta decay?
- What is Q beta value, what is its relevance to antineutrino analysis?
- Where are antineutrinos coming from?
- Why are they useful for global HPE analysis?

Nuclides & Isotopes

Nuclides:

Stable and Unstable (Radioactive)

Unstable nuclides:

Artificially produced

Naturally occurring in the Earth

Radioactive and naturally occurring in the Earth:

Radioactive isotopes decay to stable nuclides.

Apparently stable (compared to the age of the Earth) long-lived radioactive isotopes which decay by negative beta decay – generate antineutrinos in the entire Earth.

Those are the “antineutrino radiations”, that are useful for HPE analysis.

Notation of Atomic Nucleus Symbology

Material

Compounds

Elements

Atoms

(Neutrons + Protons) + Electrons

{Nucleus}

Element X is depicted by

$${}^{A}_{Z}X_{N}$$

A = Mass Number

N = Neutron Number

Z = Atomic Number (Proton Number)

$$A = Z + N$$

Radio-nuclides & Radio-isotopes

Nuclides: Characterized predominantly by atomic number Z.
Nuclide mass number is A, neutron number is N.

Isomer: Nuclide with same N, Z, A; but the nuclide exists in an excited state , called meta stable state denoted by letter 'm', for a period of time.

Ex: ${}^{235m}_{92}U_{143}$ (T ½ = 26 m) and ${}^{235}_{92}U_{143}$ (T ½ = 0.7038 x 10^9 y).

Isotope: Nuclide with same Z number, but different N.
Some of Uranium isotopes are:

Ex: ${}^{234}_{92}U_{142}$, ${}^{235}_{92}U_{143}$, ${}^{238}_{92}U_{146}$.

Chart of the nuclides provides information on isotopes of all the elements.

Gamma Decay

- When an excited nucleus de-excites, gamma rays are emitted.
- Gamma ray or gamma photon is electromagnetic radiation.
- Gamma rays have energies which may be continuous or discrete.

Alpha Decay

Alpha decay followed by gamma decay:

Alpha particle consists of two protons and two neutrons, with total mass number 4.

$$ {}^{234}_{92}\mathrm{U}_{142} \rightarrow {}^{230}_{90}\mathrm{Th}_{140} + \alpha + \gamma . $$

The unstable isotope ${}^{234}_{92}\mathrm{U}$ decays to ${}^{230}_{90}\mathrm{Th}$ by alpha and gamma radiation.

The atomic number decreases by 2 and mass number by 4.

Beta Decay

Beta decay is of two types:

- Negative beta decay
- Positive beta decay

Negative Beta decay

A neutron, n, in an unstable nucleus becomes a proton, p, emitting an electron, e^-, and an antineutrino, denoted by greek letter ν_e with a bar on the top, pronounced as nu e bar.

$$n \rightarrow p + \beta^- + \overline{\nu}_e$$

β^-, e^- are both symbols for negative beta particle or negatron.

Negative Beta decay of ^{40}K to ^{40}Ca

Z							
20	Ca 37 0.181 s	Ca 38 0.440 s	Ca 39 0.859 s	Ca 40 96.941	Ca 41 1.3E5 y	Ca42 0.647	
19	K 36 0. 342 s	K 37 1.23 s	K 38 0.926 s | 7.63 m	K 39 93.258	K 40 1.28E9 y 0.012	K 41 6.73	
18	Ar 35 1.77 s	Ar 36 0. 337	Ar 37 34.8 d	Ar 38 0.063	Ar 39 269 a	Ar 40 99.60	
	17	18	19	20	21	22	N

Table: Negative Beta decay of ^{40}K to ^{40}Ca
(shown in the format of chart of nuclides).
The atomic number Z increases by 1.
The neutron number N decreases by 1.
The mass number A remains unchanged.

Positive Beta decay

A proton, p, in an unstable nucleus becomes a neutron, n, emitting positive electron e^+ and a neutrino ν_e

$$p \rightarrow n + \beta^+ + \nu_e$$

β^+, e^+ are both symbols for positive beta particle or positron.

Positive Beta decay of ^{40}K to ^{40}Ar

Z							
20	Ca 37 0.181 s	Ca 38 0.440 s	Ca 39 0.859 s	Ca 40 96.941	Ca 41 1.3E5 y	Ca42 0.647	
19	K 36 0. 342 s	K 37 1.23 s	K 38 0.926 s | 7.63 m	K 39 93.258	K 40 1.28E9 y 0.012	K 41 6.73	
18	Ar 35 1.77 s	Ar 36 0. 337	Ar 37 34.8 d	Ar 38 0.063	Ar 39 269 a	Ar 40 99.60	
	17	18	19	20	21	22	N

Table: Beta decay of ^{40}K to ^{40}Ar (shown in the format of chart of nuclides).

The atomic number Z decreases by 1.

The neutron number N increases by 1.

The mass number A remains unchanged.

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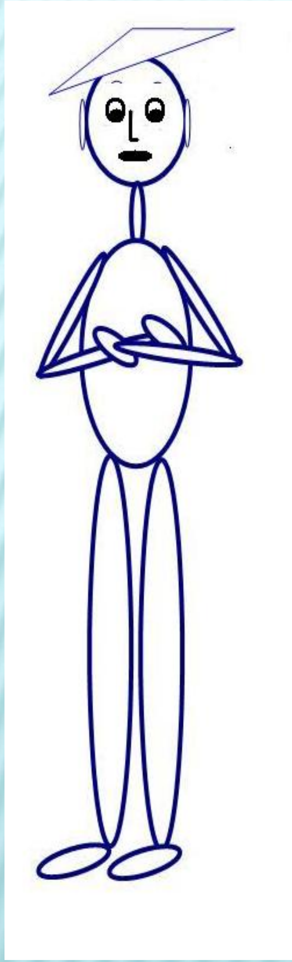


Basic Radiation characteristics of heat producing elements (HPE) :

Decay characteristics of ^{40}K

Decay Series of Uranium and Thorium

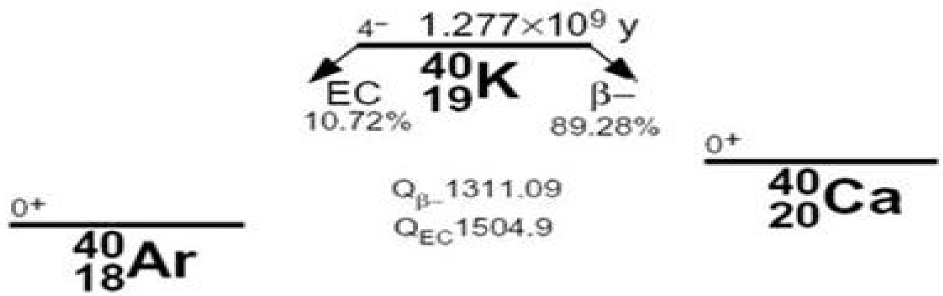
Positive and Negative Beta Decay of ^{40}K

Elemental potassium consists of three isotopes of which ^{40}K has isotopic abundance of 0.012 %, is radioactively unstable and decays with a half-life of 1.28 billion years. Both antineutrinos and neutrinos are emitted correspondingly in the negative and positive beta decay in the following proportions.

- $^{40}K \rightarrow {}^{40}Ca + \beta^- + \overline{\nu}_e$ 89.3% of decays
- $^{40}K \rightarrow {}^{40}Ar + \beta^+ + \nu_e$ 10.72% of decays

Positive and Negative Beta Decay schematic of ^{40}K

0.0117% ^{40}K isotopic abundance



89.28% Q_{β}=1.311 MeV

10.72% Q_{EC}=1.505 MeV

10.67% to 1.461 MeV state (E_{ν} = 44 keV)

0.05% to g.s. (E_{ν} = 1.5 MeV)

Figure.

Radioactive decay properties of Potassium - 40

Ref. Table of Isotopes, Seventh Edition, Ed. Lederer & Shirley

Positive and Negative Beta decay of ^{40}K

Table: Beta decay of ^{40}K (in the format of chart of nuclides).

Z ↓							
20	Ca 37 0.181 s	Ca 38 0.440 s	Ca 39 0.859 s	Ca 40 96.941	Ca 41 1.3E5 y	Ca42 0.647	
19	K 36 0. 342 s	K 37 1.23 s	K 38 0.926 s | 7.63 m	K 39 93.258	K 40 1.28E9 y 0.012	K 41 6.73	
18	Ar 35 1.77 s	Ar 36 0. 337	Ar 37 34.8 d	Ar 38 0.063	Ar 39 269 a	Ar 40 99.60	
	17	18	19	20	21	22	← N

Negative beta decay $^{40}K \rightarrow {}^{40}Ca + \beta^- + \overline{\nu_e}$ 89.3% of decays

Positive beta decay $^{40}K \rightarrow {}^{40}Ar + \beta^+ + \nu_e$ 10.72% of decays

Decay Series of U and Thorium

Uranium and Thorium decay series are well established and information is readily available in literature.

Reference:

Chapter 16.2: Genealogy of nuclides which emit α rays, p. 517-523.

The Atomic Nucleus,

by R. D. Evans

http://www.archive.org/details/atomicnucleus032805mbp.pdf

Additional information about antineutrinos

Types of Neutrinos –explanation of the subscript

- **Electron, Muon, and Tau Neutrinos**

$$\nu_e \qquad \nu_\mu \qquad \nu_\tau$$

- **Corresponding Electron, Muon, and Tau antineutrinos**

$$\overline{\nu_e} \qquad \overline{\nu_\mu} \qquad \overline{\nu_\tau}$$

Basics of radiation detection concepts

What is the implication of continuous energy of beta spectrum to the antineutrino analysis?

- The shape of the beta spectrum varies for beta decay from different isotopes.
- The peak (number of particles) may not always be at the center of the spectrum but may be off centered.
- So depending on where the detector threshold energy is with respect to the energy where the peak occurred, the detection efficiency varies.

So the focus is on the threshold energy of the detector and the detection of the beta rays or antineutrinos. It effects the overall efficiency from the detection point of view.

Energy spectrum of beta particles

- Alpha rays have discrete energies.
- Gamma rays have

  discrete and also may have continuous energies.
- Beta rays have continuous energies.

  Continuous energy spectrum of the beta rays is shown in the figure.

  The maximum energy E_{max} corresponds approximately to Q_{β} (slide 27)

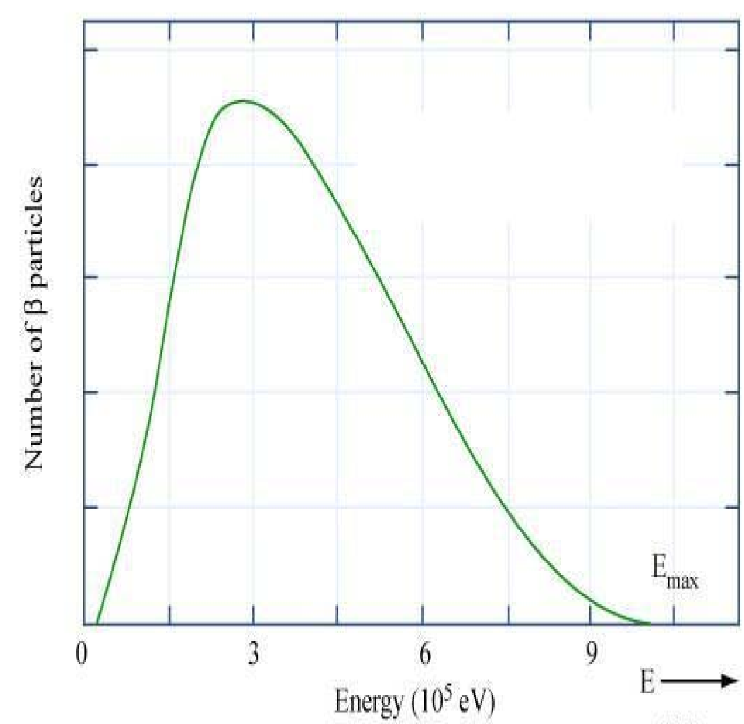


Figure. Energy Spectrum of the β rays from ^{210}Bi

Ref.: C. D. Ellis and W. A. Wooster
Proc. Roy. Soc. (London), 1927, A117, 109

Ref. p. 273 Subatomic Physics, Frauenfelder & Henley

Q_{β^-} Value

- $Q_{\beta^-} = {}_{Z}M - {}_{Z+1}M$ to a first approximation

where

${}_{Z}M$ and ${}_{Z+1}M$ are neutral atomic masses of parent and product of negatron β decay.

T_{max}= measured maximum kinetic energy or "end point" energy of the continuous beta ray spectrum

T_{γ} = Total gamma ray energy emitted after beta ray.

1 amu = 1 atomic mass unit = 931 MeV.

- http://www.nndc.bnl.gov/qcalc/qcalcr.jsp

Q_{β^-} Value continued

Why is Q_{β^-} value important?

Where does it play a role?

- **Q_{β^-} value becomes important in the detection methodology.**
- **The detection threshold energy is the minimum energy required for the detection nuclear reaction to happen, in the detector medium.**
- **If the reaction threshold energy > Q_{β^-} , the corresponding betas, in turn the corresponding antineutrinos cannot be detected when they interact with the detector medium.**

K, U, Th isotopes
Half lives, isotopic abundances

- The isotopes of the elements K, U and Th are long-lived and radioactive.
- The next Table lists, end decay products of U and Th decay series, the total Q value available, the maximum beta- energy and the corresponding values of ^{40}K decay. Half-lives and isotopic abundances of the parent nuclide are also listed.
- The half-lives and isotopic abundances parameters will be used in the antineutrino flux determinations by antineutrino analysis.

Half lives, Isotopic abundances, Q values, Beta maximum Energies Of K, U, Th radiogenic isotopes

Predominant Radiogenic Sources Decay	Half – life (10^9 yr)	Isotopic Abun-dance %	Q Total (MEV)	Beta Maximum Energy (MeV)
$^{238}U \rightarrow ^{206}Pb + 8\,^4He + 6e + 6\bar{\nu}$	4.47	99.27	51.7	3.26
$^{232}Th \rightarrow ^{208}Pb + 6\,^4He + 4e + 4\bar{\nu}$	14.0	100.0	42.8	2.25
$^{40}K \rightarrow ^{40}Ca + e + \bar{\nu}$	1.28	0.012	1.32	1.31

Ref.: G. Eder,
Terrestrial antineutrinos, Nuclear Physics, 1966, 78, 657- 662.

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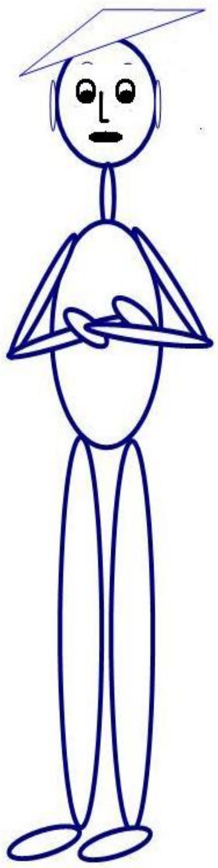


Basics of Radiation Detection Concepts:

1. Interaction of radiation with the detection medium
2. Detection signal: Charge collection
3. Detection signal: Charge collection to pulse formation
4. Energy resolution
5. Detection efficiency and solid angle
6. Basic components of a radiation detection spectrometer

Basics of radiation detection concepts

Radiations can be categorized broadly as

- Charged particle radiations:
  - Heavy charged particles
  - Fast electrons
- Neutral radiations:
  - Neutrons
  - X-rays and Gamma rays
  - Neutrinos and antineutrinos

Basics of radiation detection concepts

How is radiation, like for example alpha, beta, gamma, neutron, antineutrino detected?

- A detector is a device which detects the incident radiation.
- Initially, the energy of the incident radiation is converted to a charge pulse.
- For practical purposes, the deposition of energy of the incident radiation can be considered instantaneous.
- The net result of the interaction in a wide variety of detectors is the appearance of a given amount of electric charge in the active volume of the detector.
- For this to happen, the incident radiation should be absorbed by being stopped or attenuated in the detection medium.

Basics of radiation detection concepts

1. Interaction of radiation with the detection medium:

- Detection of a radiation by a detector depends basically on the fundamental mechanism by which that radiation interacts and loses (deposits) energy in the detection medium.
- Charged particles lose their energy in the medium by continuously interacting through coulomb force because of their charge, with the electrons of the medium.
- Neutral particles lose their energy in the medium by nuclear reactions.

Basics of radiation detection concepts

1. Interaction of radiation with the detection medium:

- Neutral particles, interact through nuclear reactions, usually with the nuclei of the atoms of the detection medium.
- If the interaction does not happen within the detector medium, then the uncharged radiations cannot be detected.
- Thus, interaction with the detection medium and energy transfer to the medium define the detection of charged or uncharged radiations.

Basics of radiation detection concepts

1. Interaction of radiation with the detection medium:

- Range for charged particles, like for example alpha represents a distance beyond which the particles cannot go further or penetrate in the detection medium.
- Stopping power for charged particles in a given absorber is defined as the ratio of the differential energy loss and the corresponding differential length travelled.

Basics of radiation detection concepts

1. Interaction of radiation with the detection medium:

- Alpha particles, have characteristic ranges in the detection media.
- Beta particles have continuous energy spectrum. They have range of energies up to a definite, characteristic maximum value.
- Beta ray absorption in the detection medium is exponential. The fractional transmission decreases exponentially but finally reaches zero, with increased thickness of the detection medium. That value of the thickness equals the maximum range, characteristic of those beta particles.

Basics of radiation detection concepts

1. Interaction of radiation with the detection medium:

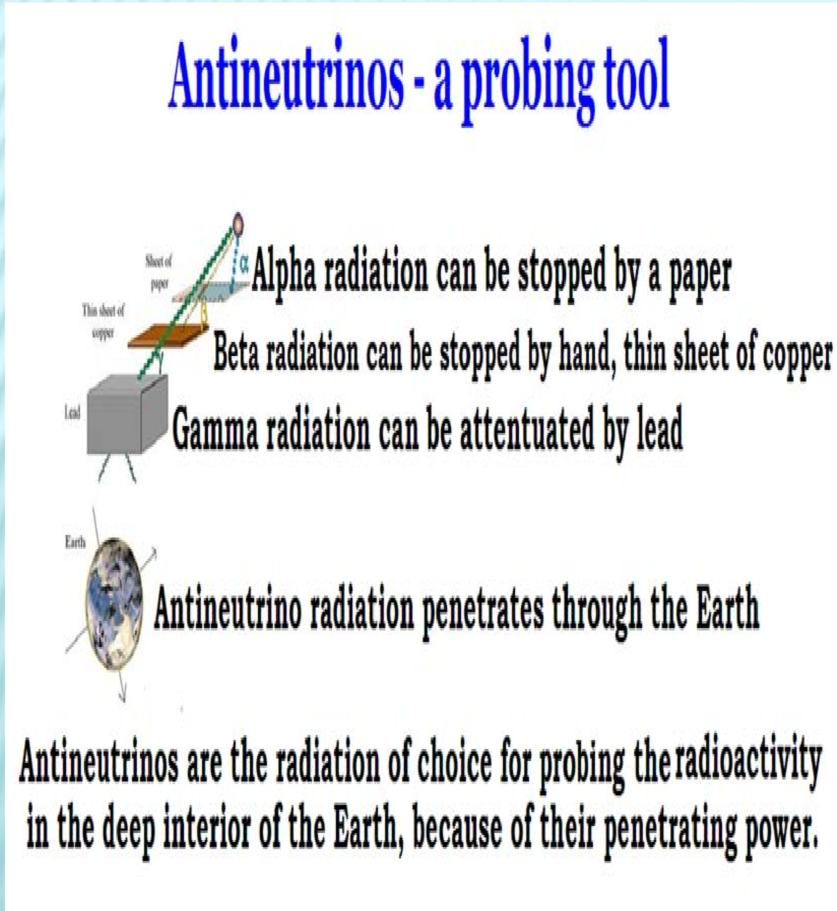
- Gamma rays, which are neutral, interact with the detection medium, predominantly by three major types of interactions called photo electric absorption, Compton scattering and pair production. Gamma rays get attenuated in the detection medium.
- Neutrons, which are neutral particles, interact with the nuclei of the detection medium. In this process, the neutrons either may lose their energy and change the direction of their path, or they may disappear completely by generating one or more secondary radiations.
- In contrast to gamma rays, the resulting secondary radiations are mostly heavy charged particles, which can then be detected directly.

Basics of radiation detection concepts

1. Interaction of radiation with the detection medium:

- Antineutrinos interact weakly with any matter. That is the main reason, even the antineutrinos generated in the deep interior of the Earth reach the surface of the Earth.
- However, antineutrinos interact weakly with the detector medium as well. Hence the probability of their detection is very low relative to, for example gamma rays. Thus, they need very large volume detection medium.

Basics of radiation detection concepts



- Alpha particles travel very short distances in materials, often less than 100 micrometers in solid low-atomic-number materials.
- Beta particles are more penetrating, many of them able to travel a few millimeters in low-atomic-number solid materials.
- Gamma radiation is quite penetrating and depending on its energy, can penetrate through tens of centimeters thickness of lead large thicknesses of high atomic number solid materials like lead
- Neutron path length , several meters ,in a detection medium is strongly dependent on the energy of the neutron,
- Antineutrinos are capable of penetrating 12,000 kilometers, the entire diameter of the Earth.

Basics of radiation detection concepts

1. Interaction of radiation with the detection medium:

- Thus, the stopping power of the detection medium determines the efficiency of the detector.
- Stopping power parameter is dependent on the energy of the radiation.

Basics of radiation detection concepts

2. Detection signal: Charge collection

Assume a hypothetical detector exposed to some type of radiation.

Consider first a single particle or quantum of radiation that enters the detection medium. This single particle could be for example a single alpha particle or gamma ray photon.

In order for the radiation to be detected, the detector medium must respond by interacting with the radiation particle which has certain amount of energy.

Basics of radiation detection concepts

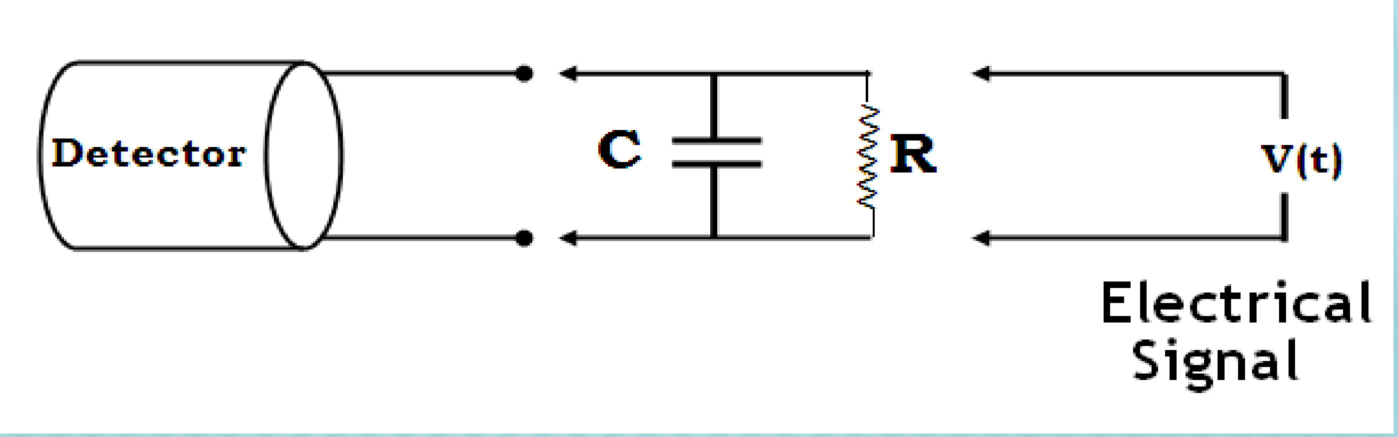
2. Detection signal: Charge collection

- Thus a charge Q appears within the detector at the time t = 0 due to interaction of a single particle or quantum of radiation.
- This charge Q must be collected to form the basic electric signal, which is accomplished by the imposition of an electric field within the detector which causes the positive and negative charges created by the radiation to flow in the opposite directions.

Basics of radiation detection concepts

2. Detection signal: Charge collection

- If the charge is collected for a time period t_c , the time integral over the duration of the current must be equal to Q, the total amount of charge generated in that specific interaction.
- Detector model schematic



Basics of radiation detection concepts

3. Detection Signal : Charge collection to Pulse formation

The next step of operation in the detector is fundamentally of two distinct types:

- Current mode of operation
- Pulse mode of operation.
- Current mode represents in which the average dc current produced by the detector is measured.
- Pulse mode – instead of looking at the average current over many interactions, the output is recorded for each individual quantum of radiation which happens to interact with the detector medium.

Basics of radiation detection concepts

3. Detection Signal : Charge collection to Pulse formation

When operating a radiation detector in pulse mode, each individual pulse amplitude carries important information regarding the charge generated by that particular radiation interaction in the detector.

- The amplitudes will be different for a large number of pulses, due to difference in incident radiation energy or to fluctuations in inherent response of the detector to the incident radiation.
- The pulse amplitude distribution is a fundamental property of the detector output which provides important information about the incident radiation or the operation of the detector itself.

Basics of radiation detection concepts

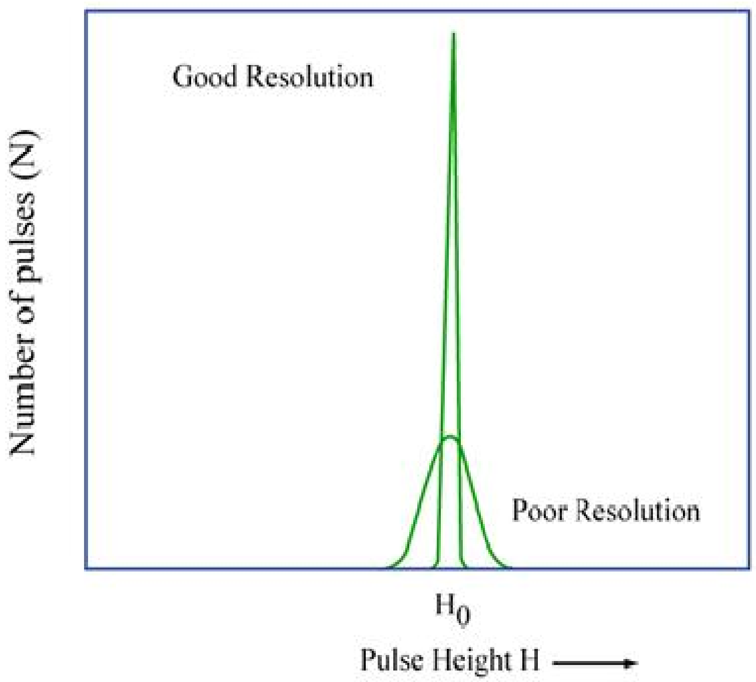
4. Energy Resolution:

In radiation spectrometry, the main object is measurement of the energy distribution of the incident radiation.

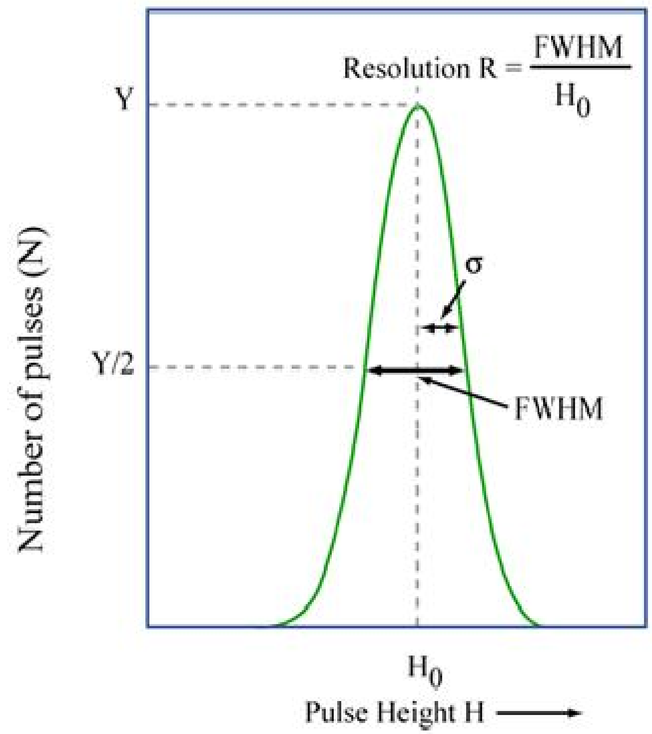
- Full Width Half Maximum FWHM
- Pulse Height at maximum H_0
- Resolution $R = FWHM / H_0$
- How closely the adjacent incident energies can be detected, is measured by energy resolution parameter·

Basics of radiation detection concepts

4. Energy Resolution:



Pictorial depiction of relatively poor and good resolution of detector signal.



Pictorial depiction of energy resolution definition.

Basics of radiation detection concepts

5. Detection Efficiency and Solid Angle

- **Absolute Efficiency**

E_{abs} = number of pulses recorded/ number of radiation quanta emitted by source

- **Intrinsic Efficiency**

E_{int} = number of pulses recorded / number of quanta incident on detector

Basics of radiation detection concepts

5. Detection Efficiency and Solid Angle

$E_{int} = E_{abs}\, 4\pi/\Omega$

- Where Ω is the solid angle of the detector seen from the actual source position.
- Intrinsic efficiency of the detector depends primarily on the detector material, the radiation energy, and the physical thickness of the detector in the direction of the incident radiation. A dependence on the distance between the source and the detector remains.

Basics of radiation detection concepts

5. Detection Efficiency and Solid Angle

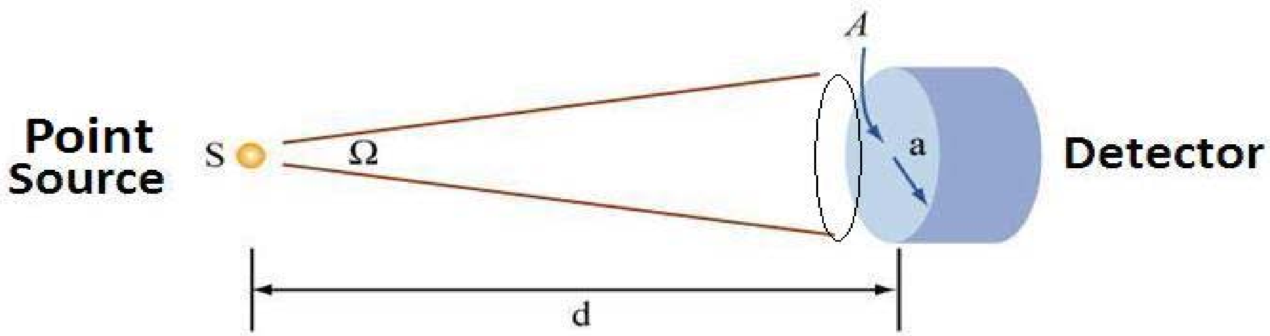


Figure. Pictorial depiction of sloid angle subtended between source and detector.
Source size is smaller relative to the detector size.

Solid Angle $\Omega \cong \frac{A}{d^2} = \frac{\pi a^2}{d^2}$

where the source-detector distance d and detector radius a are shown in the sketch.
For $d >> a$, the solid angle reduces to the ratio of the detector plane frontal area A visible at the source to the square of the distance

Image by MIT OpenCourseWare.

5. Detection Efficiency and Solid Angle

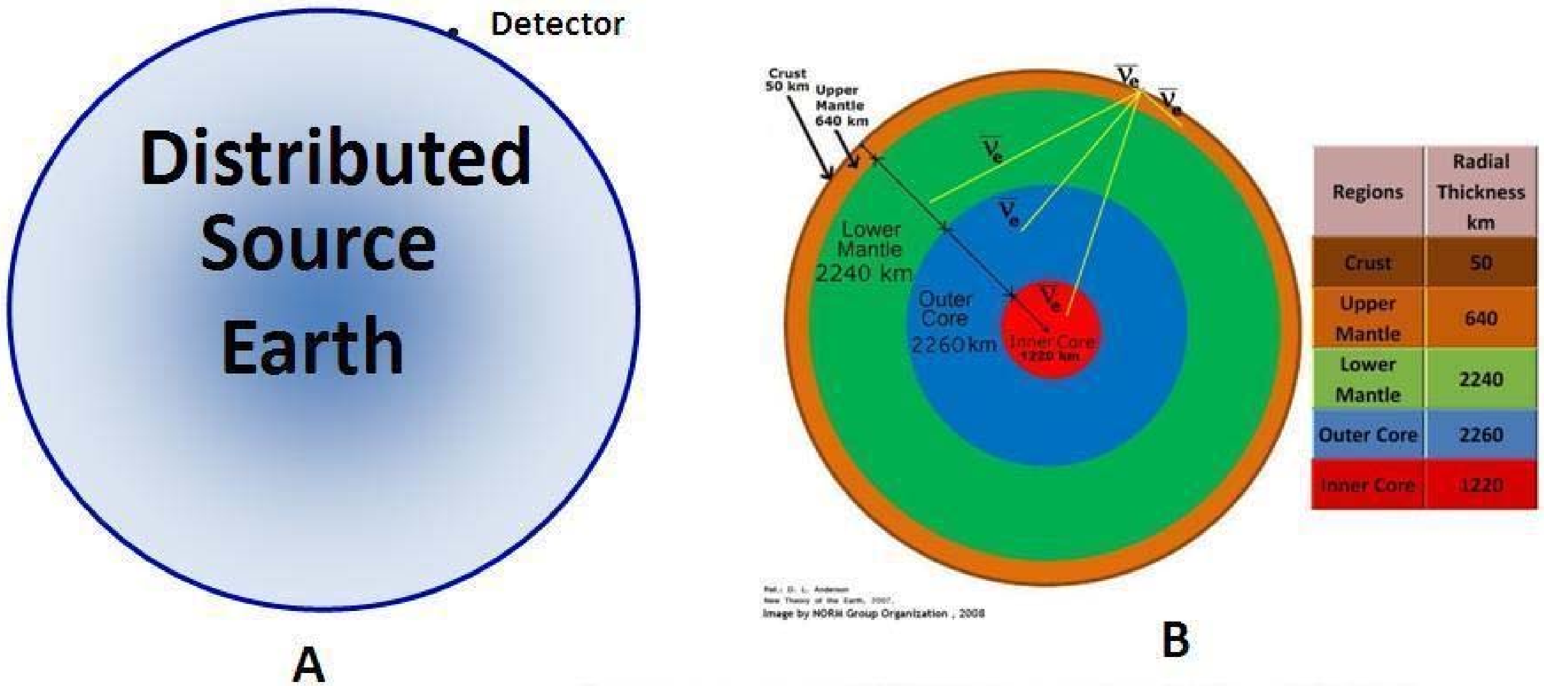
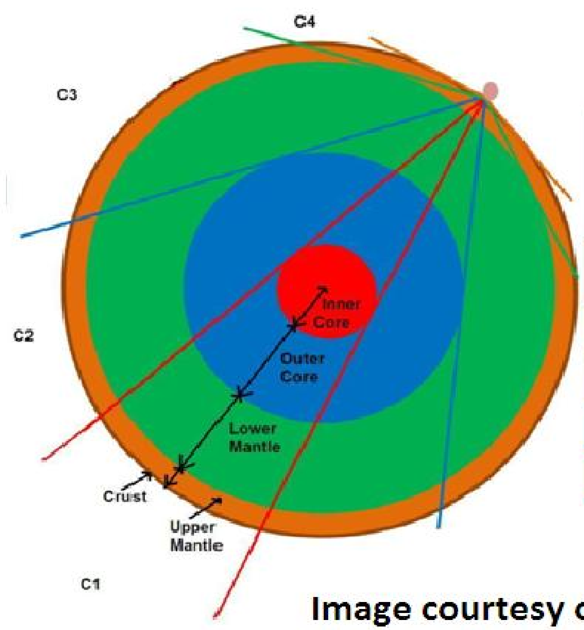


Figure.
A. Pictorial visualization of relative sizes of source and detector.
B. Pictorial visualization of the solid angle subtended from different regions of the Earth.

Image courtesy of NORM Group Organization, Cambridge, MA, USA. **Used with permission**

Basics of radiation detection concepts



Regions	Radial Thickness km
Crust	50 - 70
Upper Mantle	640
Lower Mantle	2240
Outer Core	2260
Inner Core	1220

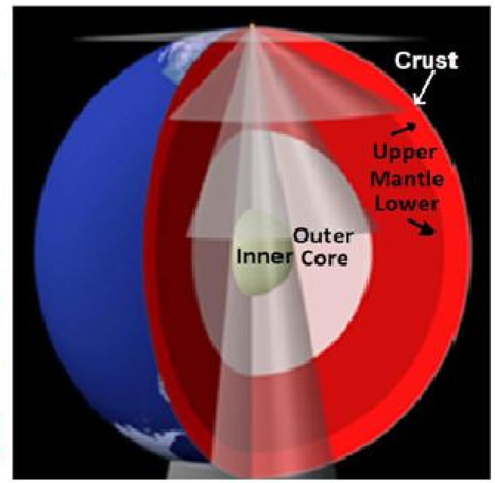


Image courtesy of NORM Group Organization, Cambridge, MA, USA.
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Figure. Conceptualization of solid angle between source (Earth) and detector located on/in the crust

Solid angle parameter is of significant importance in antineutrino analysis, with reference to the antineutrino detector located on crust, because of the large dimensions of the Earth regions compared to the detector size.

Basics of radiation detection concepts

5. Detection Efficiency and Solid Angle

- A detector with known efficiency can be used to measure the absolute activity of a radioactive source
- Assumption: Source emits radiation isotropically and no attenuation takes place between source and detector.
- Solid angle parameter is of significant importance in antineutrino analysis.

6. Basic components of a radiation detection spectrometer:

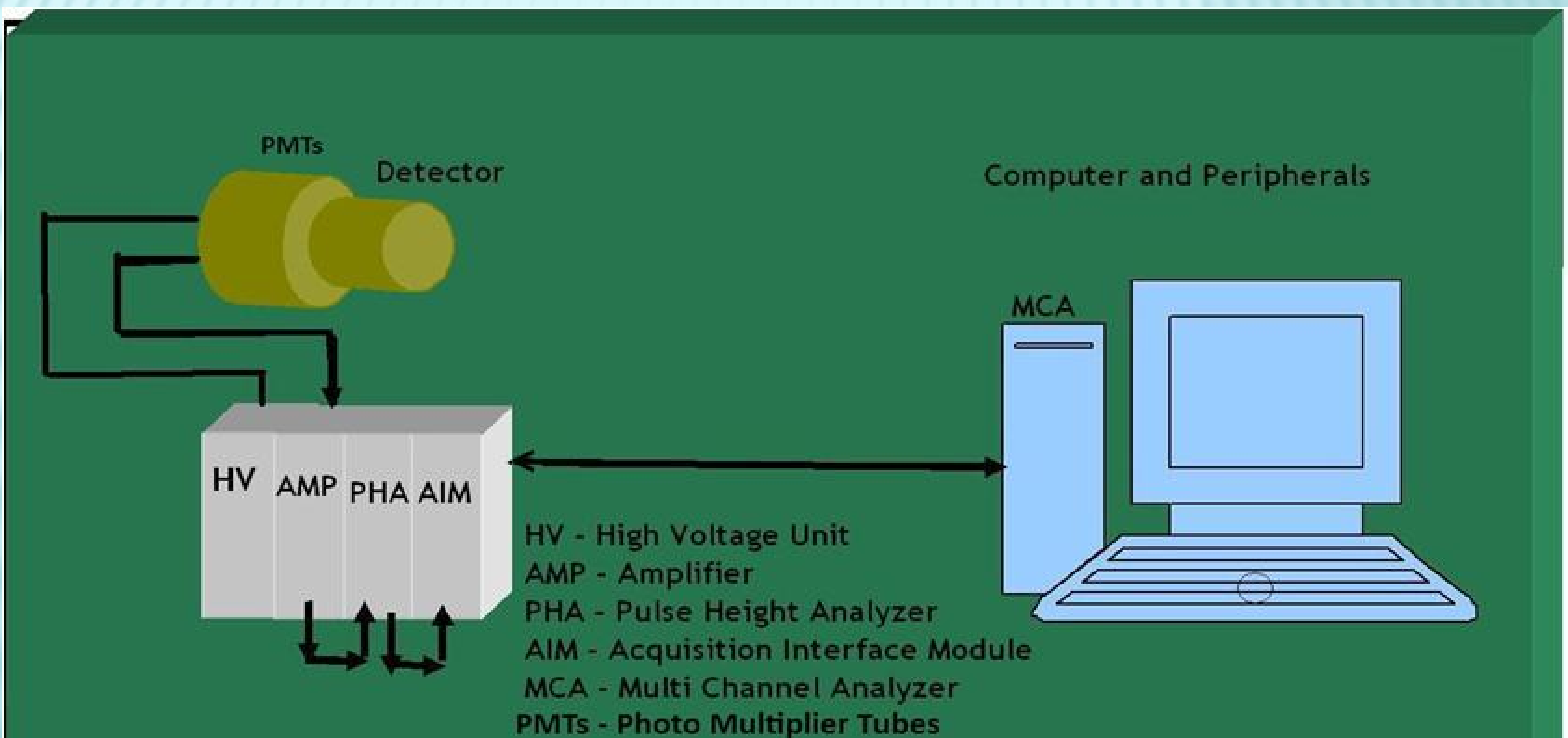
Radiation detection spectrometer for measuring the incident radiation, typically consists of:

1) Detector (detecting (target) medium)
2) Transducer (Photo Multiplier Tubes optional)
3) Preamplifier and Amplifier
4) Pulse Height Analyzer
5) Multi Channel Analyzer
6) Computer & peripherals

Figure in the next slide shows pictorially the components of a radiation detection spectrometer.

Basics of radiation detection concepts

Figure. Basic components of a radiation detection spectrometer



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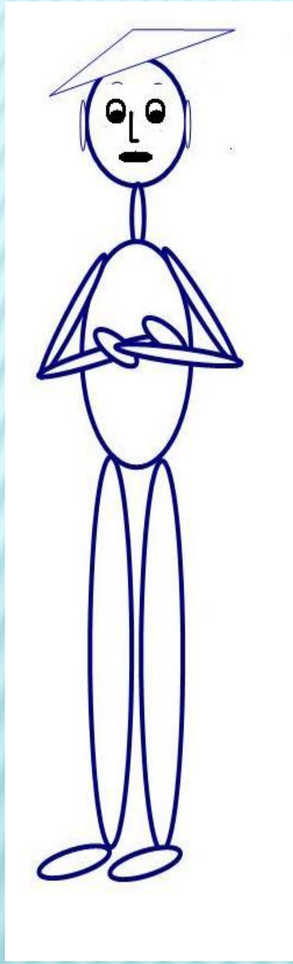
Summary of radiation detection concepts



- Types of radiation.
- Interaction of radiation with the detection medium

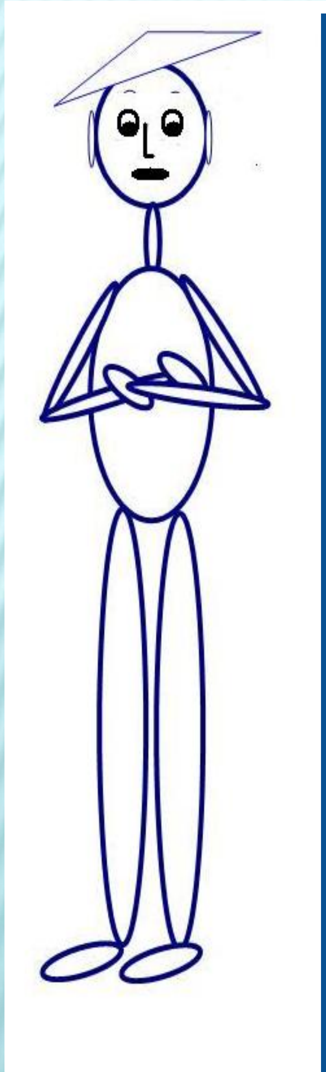
Concepts of

- stopping power of the medium
- penetration range of the incident radiation in the medium.

Simplified detector model

- Deposition of energy and charge collection
- Conversion of charge to signal pulse
- Energy resolution and efficiency of the detector
- Solid angle parameter of the incident radiation
- Relevance of the solid angle parameter in the analysis of Earth's K, U, Th determination

So far talked about

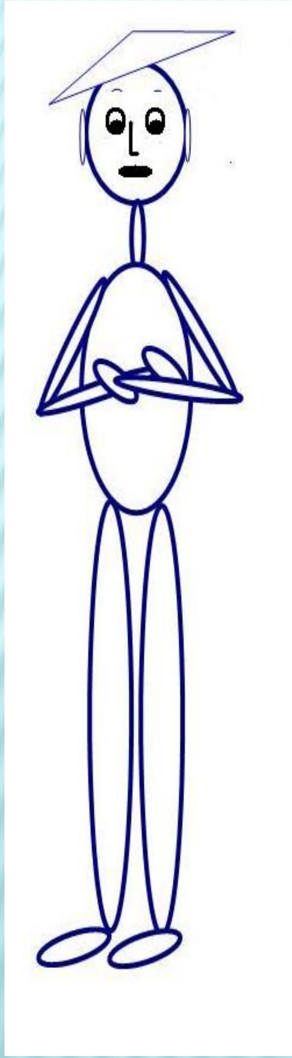


Basics of Radiation Detection Concepts:

1. Interaction of radiation with the detection medium
2. Detection signal: Charge collection
3. Detection signal: Charge collection to pulse formation
4. Energy resolution
5. Detection efficiency and solid angle
6. Basic components of a radiation detection spectrometer

So far I talked about basics of radiation detection which are also applicapble to antineutrino detection

Next proceeding to



Basics of Antineutrino Radiation Detection

Concepts:

1. Antineutrinos as probes to study Heat Producing Elements (HPE) in the deep interior of the Earth:
2. Antineutrino detection by using inverse beta decay reaction products
3. Inverse beta decay nuclear reactions for antineutrinos detection
4. Basic components of an antineutrino detector
5. Background Interferences
6. Antineutrino detection without directional sensitivity by scintillation detection
7. Antineutrino detection with directional sensitivity by Cerenkov radiation detection

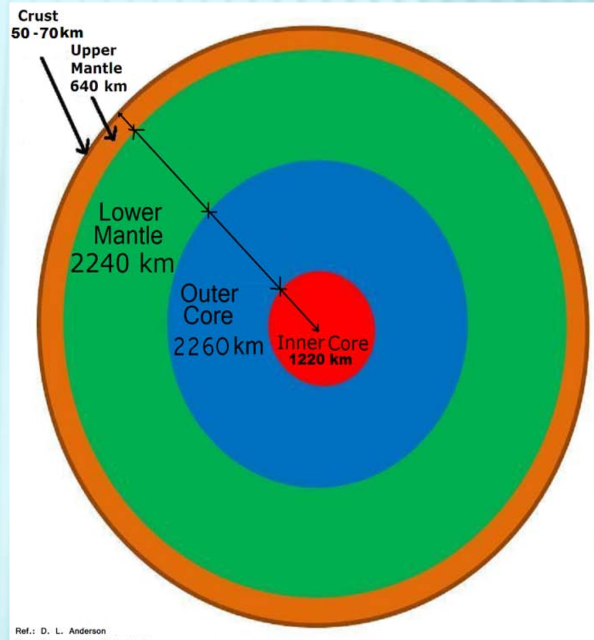
Basics of antineutrino detection concepts

1. Antineutrinos as probes to study Heat Producing Elements (HPE) in the deep interior of the Earth:

- The penetration power of antineutrinos is thousands of times higher than other radiations like alpha, beta and gamma.
- The path length of the antineutrinos is greater than the Earth's diameter.
- Hence antineutrinos generated in the deep interior of the Earth reach the surface of the Earth, and thus can be detected.

Basics of radiation detection concepts

- **Antineutrinos generated at the site of creation are detected by means of the effects they produce in a detecting medium.**
- **Because these antineutrinos reach the crust or surface of the Earth, and interact with the detector medium, we will be able to do the analysis.**
- **This is the key point in the determination of Heat Producing Elements (HPE) in deep interiors of the Earth by the antineutrinos they emanate.**
- **Such an analysis cannot done by using alpha, beta, gamma rays coming from the HPE located in the deep interior of the Earth.**



Regions	Radial Thickness km
Crust	50 - 70
Upper Mantle	640
Lower Mantle	2240
Outer Core	2260
Inner Core	1220

Earth Regions

Image courtesy of The NORM Group Organization

Used with permission

Basics of antineutrino detection concepts

For detection of radiations like alpha, beta, gamma, neutron – the main point is that

- Their interaction with the detecting medium is strong, where as interaction of antineutrinos is weak.
- Their interaction probability with the detector medium is higher than that of a weakly interacting particle like the neutrino or antineutrino.
- Hence the detector medium has to be much higher in volume and material for the antineutrino particle detection.
- The detection concepts and parameters discussed so far are applicable to the antineutrino radiation detection except for the penetrability of the antineutrinos.

Basics of antineutrino detection concepts

2. Antineutrino detection by using inverse beta decay reaction products:

- In 1934, long before the neutrino was detected in an experiment, Fermi provided model for the beta decay process.
- The fundamental process that takes place in beta decay is the change of a neutron into a proton, an electron, and an antineutrino. The neutron may be a free particle, or it may be bound inside the nucleus.

Basics of antineutrino detection concepts

2. Antineutrino detection by inverse beta decay reaction products (continued) :

What happens when antineutrinos enter matter of the detector medium?

- Most of the time, they pass straight through without scattering, but Fermi's theory of the weak force predicts that the neutrino can induce a beta decay .
- In particular, the antineutrino (the antiparticle of the neutrino) will occasionally interact with a nucleus through the weak force and will induce the transformation of a proton into a neutron.

Basics of radiation detection concepts

2. Antineutrino detection by using inverse beta decay reaction products (continued) :

- **Negative beta decay accompanied by antineutrinos** – a neutron in an unstable nucleus becomes a proton emitting an electron and an antineutrino.

$$n \rightarrow p + \beta^- + \overline{\nu}_e$$

- **Inverse beta decay capturing antineutrinos by protons in a detector** – an incoming antineutrino interacts with a proton in the detection medium releasing a neutron and a positron.

$$\overline{\nu}_e + p \rightarrow n + \beta^+$$

Basics of antineutrino detection concepts

2. Antineutrino detection by using inverse beta decay reaction products (continued):

- This inverse of the usual beta-decay process results in a nucleus with one less unit of positive charge. The reaction products are:

  $\overline{\nu}_e$ (antineutrino) + X (n, p) → e^+ + Y (n+1, p−1) ,

- where n equals the number of neutrons and p equals the number of protons of a nucleus X. If the nucleus happens to be that of hydrogen (a single proton), then the interaction produces a neutron and a positron, e^+:

  $\overline{\nu}_e$ (antineutrino) + p → n + e^+ .

Antineutrinos are detected by detecting the inverse beta decay reaction products namely, positron and the neutron.

Basics of antineutrino detection concepts

2. Antineutrino detection by using inverse beta decay reaction products (continued) :

- Antineutrinos travel in straight lines from point A to B; unlike for example the neutrons which travel zig-zag.
- This characteristic of the antineutrinos is useful in the antineutrino analysis to develop detection directional sensitivity.

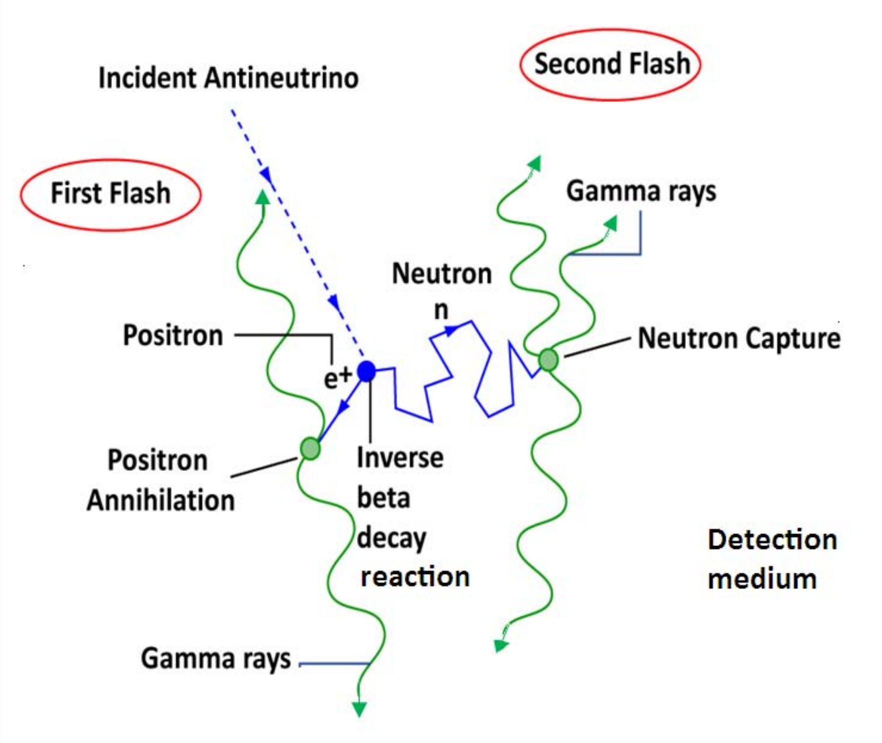


Figure. Pictorial depiction of antineutrino interaction with the detection medium.

Image by MIT OpenCourseWare.

Basics of antineutrino detection concepts

2. Antineutrino detection by using inverse beta decay reaction products (continued) :

The figure illustrates antineutrino detection principles.

Inverse beta decay reaction begins when the incident antineutrino (blue dashed line) interacts with protons in the medium.

The reaction products positron (e^+) and a neutron (n) are released.

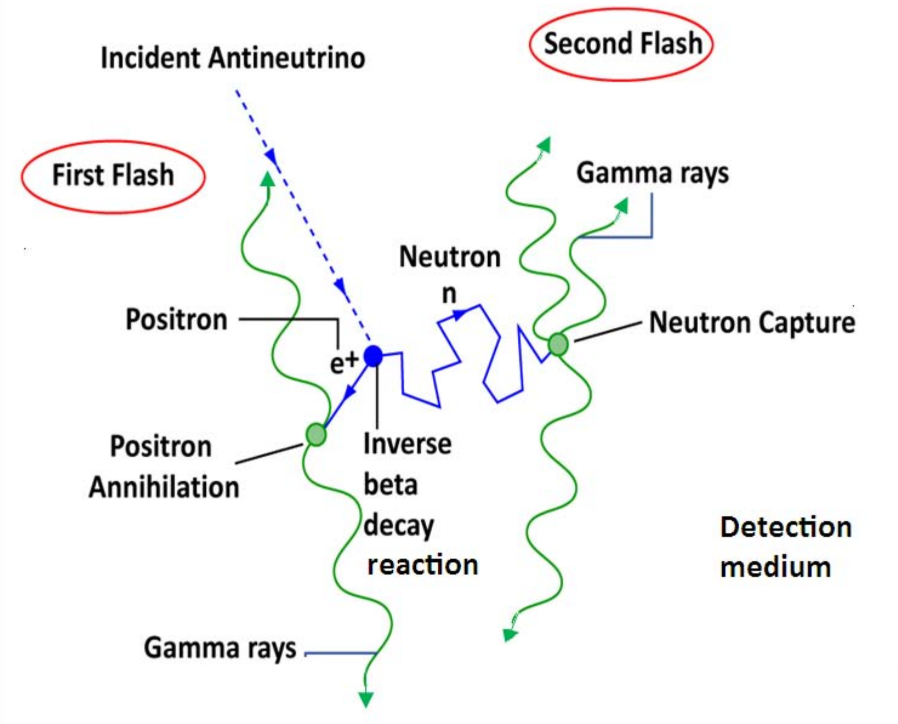


Figure. Pictorial depiction of antineutrino interaction with the detection medium.

Image by MIT OpenCourseWare.

Basics of antineutrino detection concepts

2. Antineutrino detection by using inverse beta decay reaction products (continued):

- Presence of antineutrino is confirmed by detecting both products of inverse beta decay, a reaction in which an incident antineutrino (blue dashed line) interacts with a proton through the weak force. The antineutrino turns into a positron (e^+), and the proton turns into a neutron (n).
- In the figure, this reaction is shown to take place in a liquid scintillator. The short solid blue arrow indicates that, shortly after it has been created, the positron encounters an electron, and the particle and antiparticle annihilate each other.

Basics of antineutrino detection concepts

2. Antineutrino detection by using inverse beta decay reaction products (continued):

- Two gamma rays are emitted that travel in opposite directions and will cause the liquid scintillator to produce a flash of visible light.
- In the meantime, the neutron travels further, following a random path (longer zig-zag, solid blue arrow) until it is captured. The resulting nucleus releases energy in gamma rays that will cause the liquid scintillator to produce again a tiny flash of visible light.
- This sequence of two flashes of light separated by a few microseconds is the double signature of inverse beta decay and confirms the presence of an antineutrino.

Basics of antineutrino detection concepts

2. Antineutrino detection by using inverse beta decay reaction products (continued) :

First and second flashes separated by few microseconds when detected in coincidence provide the "double signature"of inverse beta decay to confirm the detection of the incident antineutrino.

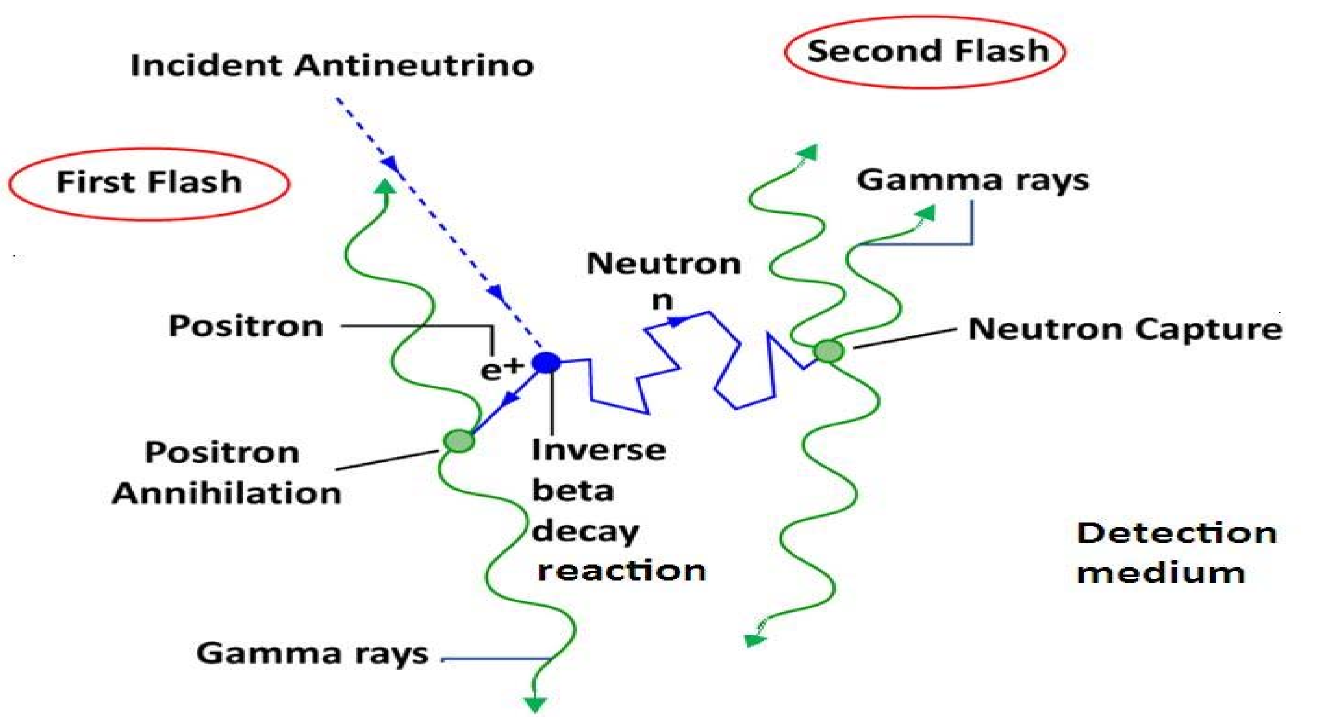


Figure. Pictorial depiction of antineutrino interaction with the detection medium.

Image by MIT OpenCourseWare.

Basics of antineutrino detection concepts

3. Inverse beta decay nuclear reactions for antineutrinos detection

Inverse beta decay

by a proton

in a detector by capturing antineutrinos – an incoming antineutrino interacts with a proton in the detection medium releasing a neutron and a positron.

Threshold energy of the reaction – 1. 8 MeV

$$\overline{\nu}_e + p \rightarrow n + \beta^+$$

Inverse beta decay

by a deuteron, d:

Threshold energy of the reaction - 4.03 MeV.

$$\overline{\nu}_e + d \rightarrow n + n + \beta^+$$

Basics of antineutrino detection concepts

3. Inverse beta decay nuclear reactions for antineutrinos detection

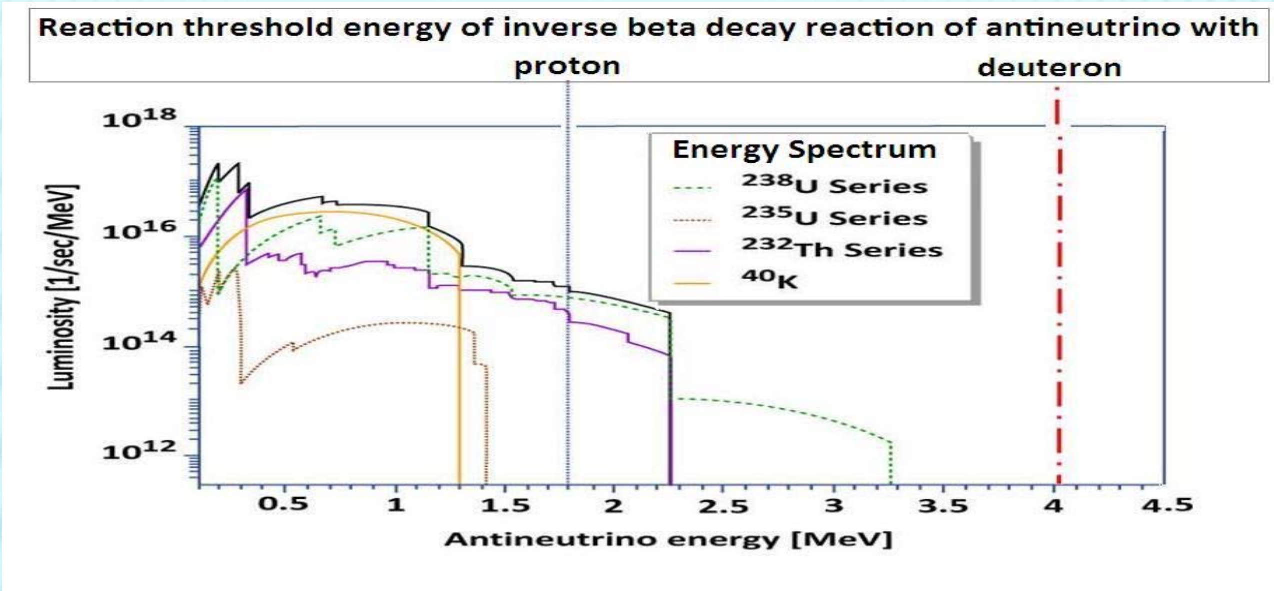


Figure. Relevance of detection threshold energy to the detection of energies of antineutrinos emitted in the decay of K, U, and Th in the Earth.

1) The vertical dotted line at 1.8 MeV represents the energy threshold of scintillation detectors employing the inverse beta decay reaction for the detection of antineutrinos. So K cannot be detected if the detection threshold is higher.

Ref. Araki et al. KamLAND Collaboration, Nature, 2005, 436, 499-503.

2) The red dash and dotted line at 4.03 MeV represents the energy threshold for detectors using deuterium for the inverse beta decay reaction. Hence K, U, Th cannot be detected with such detectors.

Basics of antineutrino detection concepts

4. Basic components of an antineutrino detector:

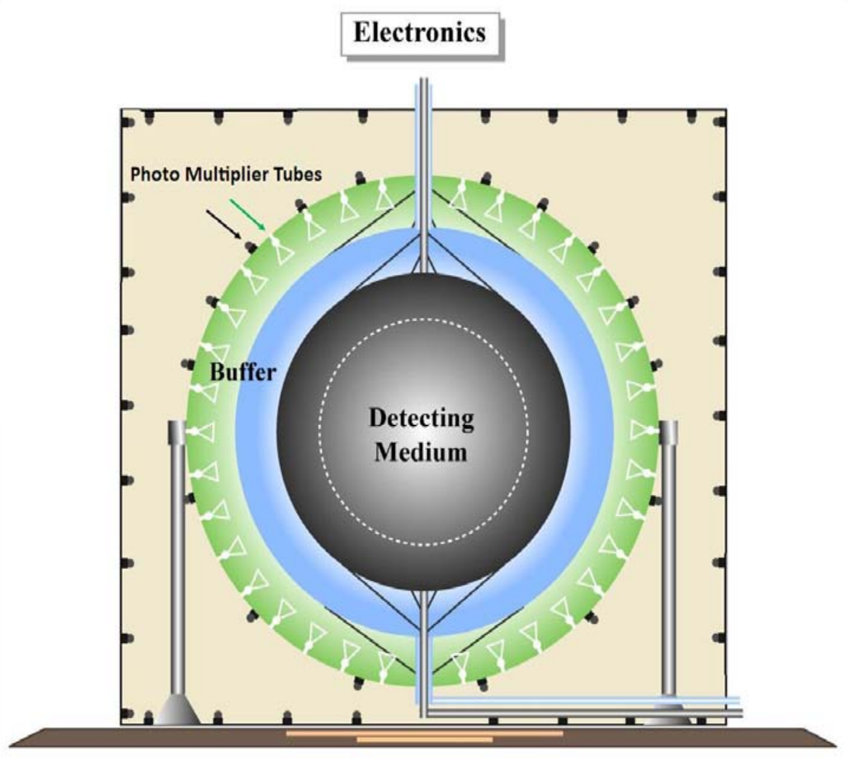


Figure. Pictorial depiction of an antineutrino detector shown in spherical shape. The configuration could be spherical, cubical or any other shape.

Ref. Figure based on the figure of KamLand detector by KamLAND collaboration

Basics of antineutrino detection concepts

4. Basic components of an antineutrino detector:

One of the ways of detection is by a liquid scintillator.

A liquid scintillator converts a fraction of the energy of the gamma rays, generated by the incident positron annihilation, into a tiny flash of light. Similarly scintillation light pulses are generated by the energy of the gamma rays emitted by the interaction of the neutrons with the scintillation medium.

The light travels through the highly transparent liquid scintillator to the surrounding photo multiplier tubes, where the photons are converted into an electronic pulse.

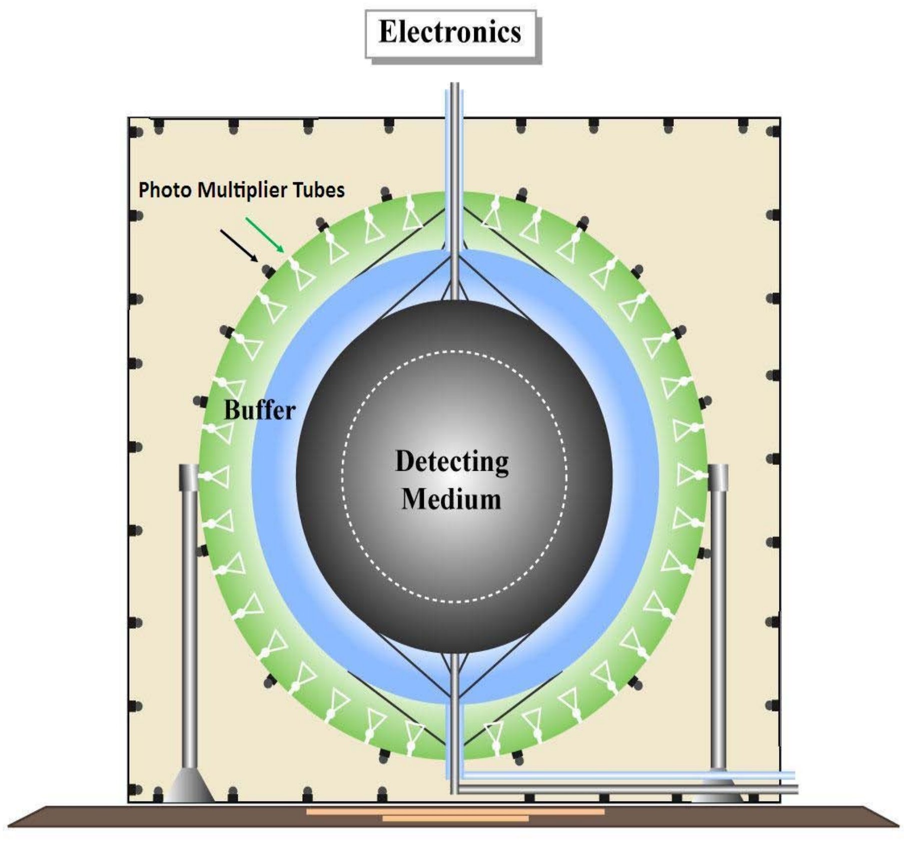


Figure. Pictorial depiction of an antineutrino detector shown in spherical shape. The configuration could be spherical, cubical or any other shape.

Ref. Figure based on the figure of KamLand detector by KamLAND collaboration

Basics of antineutrino detection concepts

5. Background Interferences :

Concept of Interference:

The incident energy of the radiation is converted into a signal pulse by the detection system.

So each pulse is representative of the incident energy.

That incident energy of the radiation corresponds to the isotope of the element of interest.

However, that pulse may also be generated by an energy of radiation not belonging to the isotope of interest. This additional contribution is thus interfering with the true pulse of interest.

Basics of antineutrino detection concepts

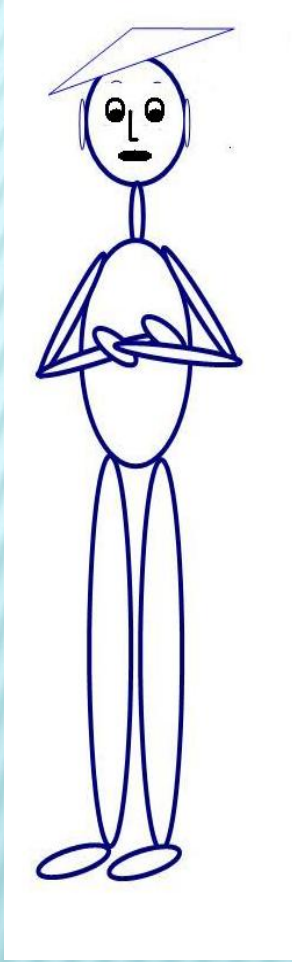
5. Background Interferences (continued) :

There are primarily four component sources in the background spectrum, interfering with the signal of interest:

1. The intrinsic Heat Producing Elements (HPE) contamination in the component materials used in the construction of the detector.
2. The cosmic ray interactions which produce signals similar to the signal of interest.
3. Power reactors and other anthropogenic sources surrounding the detector.
4. Interference from fluctuating airborne radioactivity.

These background contributions should be properly accounted in order to optimize the detection signal to background ratio not only to improve the detection sensitivity but also to measure the HPE (namely K, U, Th) abundances accurately.

Next proceeding to



Concepts of directional sensitivity of antineutrino detection

- with no or partial memory of the direction of the incident antineutrino
- with full memory of the direction of the incident antineutrino

Basics of antineutrino detection concepts

6. Antineutrino detection without directional sensitivity by scintillation detection:

- Antineutrinos are detected by inverse beta decay reaction with the detection matter.
- Inverse beta decay capturing antineutrinos by protons of detector matter – an incoming antineutrino interacts with a proton in the detection medium releasing a neutron and a positron.

$$\overline{\nu}_e + p \rightarrow n + \beta^+$$

Basics of antineutrino detection concepts

6. Antineutrino detection without directional sensitivity by scintillation detection (continued) :

- Incident antineutrino interacts with the protons of the detecting medium by inverse beta decay reaction.
- The reaction products are positron and neutron.
- These in turn generate gamma rays.
- These gamma rays are detected by the scintillating medium, which generate the light pulses; which are detected by the photo multiplier tubes which provide the signal for analysis.

Basics of antineutrino detection concepts

6. Antineutrino detection without directional sensitivity by scintillation detection (continued) :

- The final signal of the gamma rays from positron and the neutrons that are detected in coincidence provide confirmation of the incident antineutrino.
- This type of detection methodology does not sustain the information of the direction of the incident antineutrino. That information is lost partially, if not in full.
- Many investigators consider that , since in the inverse beta decay reaction, the neutron emitted most of the time is in the forward path of the incident antineutrino direction, directional information of the incident antineutrino is preserved partially if not in full.

Basics of antineutrino detection concepts

6. Antineutrino detection without directional sensitivity by scintillation detection (continued):

Currently, the preferred mode of antineutrino detection is by detection of scintillation pulses emitted by interaction of gamma-rays with the scintillator; the gamma rays are generated by the inverse beta decay reaction products neutron (n) and positron (e^+).

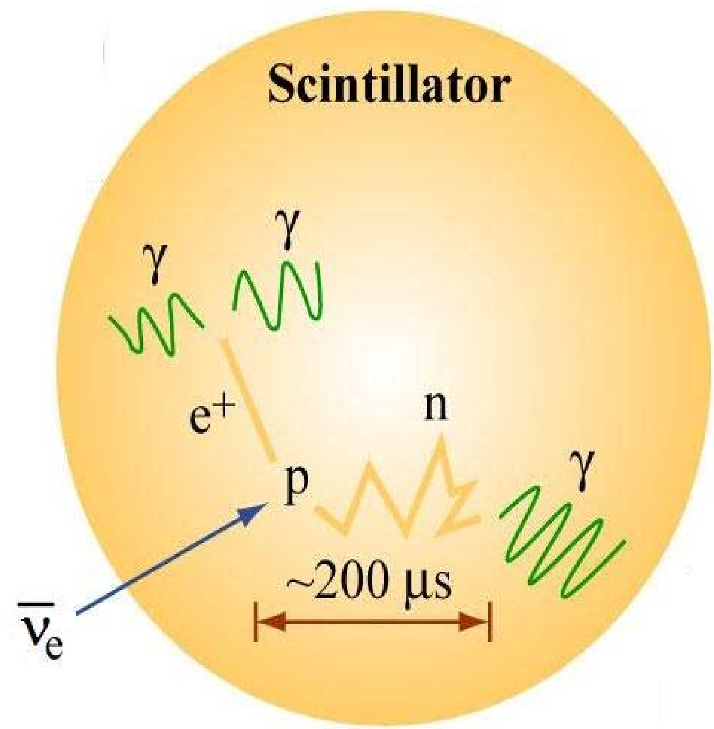


Figure.
Pictorial depiction of incident antineutrino detection by inverse beta decay reaction.

Image by MIT OpenCourseWare.

Basics of antineutrino detection concepts

7. Antineutrino detection with no directional sensitivity by scintillation detection method:

- The positron travels at relativistic velocity in the detection medium and annihilation takes place only when it eventually comes to rest and interacts with an electron, emitting two equal and opposite gamma-rays, each of energy 511 keV.
- These gamma rays will interact with the scintillating medium of the detector, scinitillation light photons will be generated. The photo multiplier tube converts the incident scintillation photon into a signal.
- The neutron travels in zig-zag path, in the detection medium, until it is captured. The resulting nucleus releases energy in gamma rays that will cause the liquid scintillator to generate scinitllation light.
- Thus in the scintillation detection method, consists of detecting the gamma rays from the reaction products namely the positron and neutron.
- The information of the direction of the incident antineutrino is lost because scintillation light resulting from the gamma rays, will be emitted **isotropically and not preferentially.**

Basics of antineutrino detection concepts

7. Antineutrino detection with no directional sensitivity by scintillation detection method (continued) :

- Incident antineutrino interacts with the proton of the detection medium by inverse beta decay reaction, emitting neutron and positron.
- The positron, travelling almost at relativistic velocity of the light, emits Cerenkov radiation.
- In contrast to the scintillation light which is emitted isotropically, Cerenkov radiation is emitted preferentially along the direction of the positron velocity, in the shape of a cone with the vertex pointing towards the direction of the incident antineutrino.

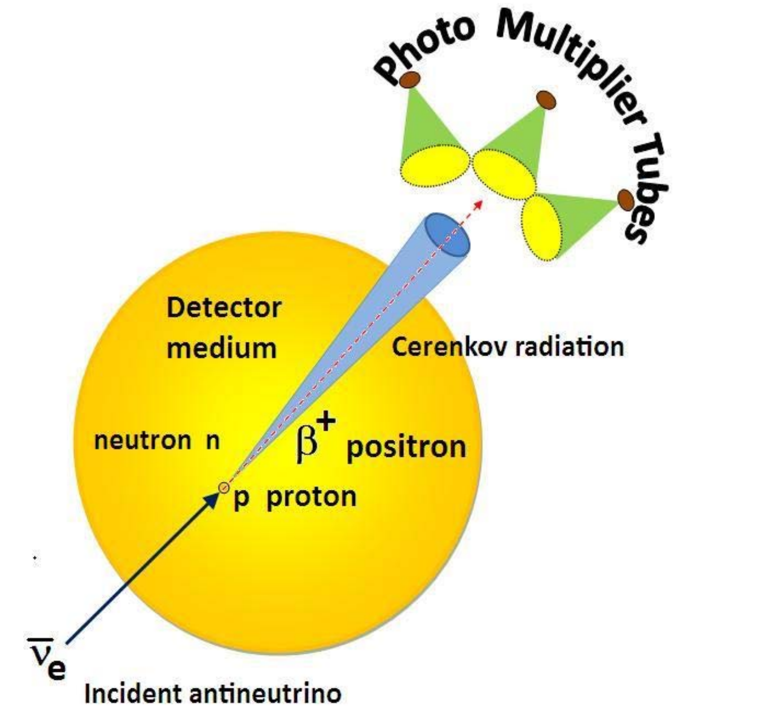


Figure. Pictorial depiction of retaining the direction information of the incident antineutrino.
Image courtesy of The NORM Group Organization, MA, USA

Used with permission.

Basics of antineutrino detection concepts

7. Antineutrino detection with no directional sensitivity by scintillation detection method (continued) :

- Direction of the incident antineutrino will be inferred by specially designed software which deduces that information by identification of the locations of the photo multiplier tubes which provide a correlated signal for the emitted Cerenkov radiation.

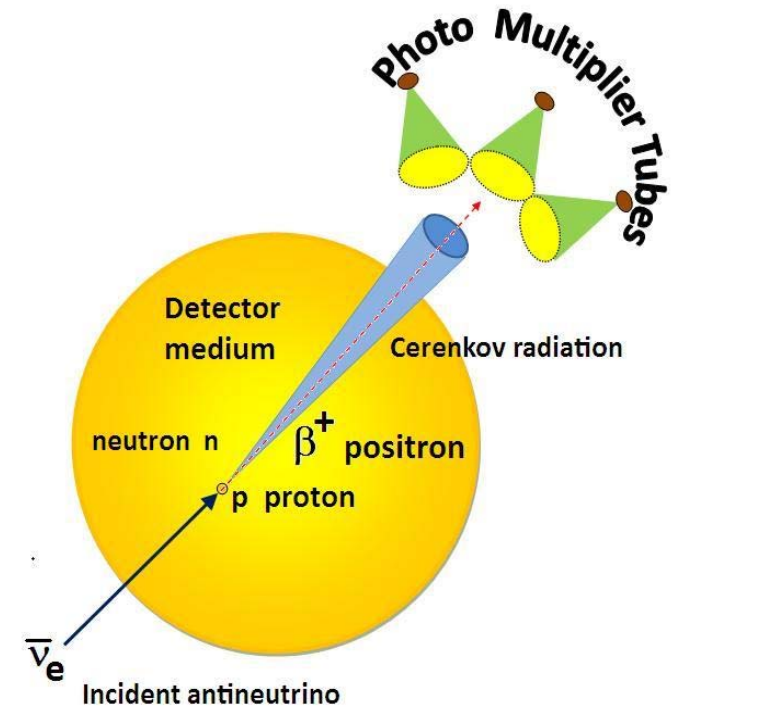


Figure. Pictorial depiction of retaining the direction information of the incident antineutrino.
Image courtesy of The NORM Group Organization, MA, USA

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Basics of antineutrino detection concepts

Antineutrino detection with no directional sensitivity

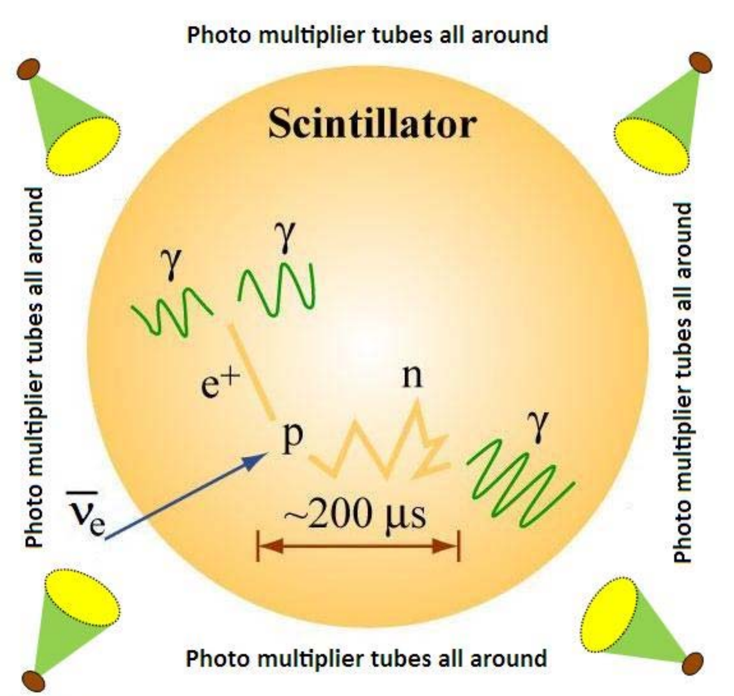


Figure.
Pictorial depiction of incident antineutrino detection by inverse beta decay reaction.

Antineutrino detection with directional sensitivity

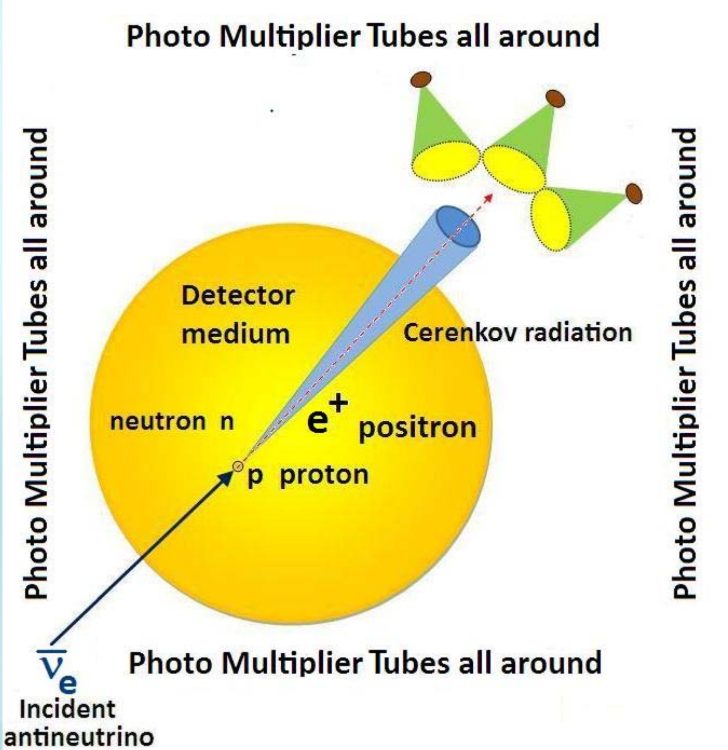


Figure. Pictorial depiction of retaining the direction information of the incident antineutrino.
Image courtesy of The NORM Group Organization, MA, USA

Used with permission.

Basics of antineutrino detection concepts

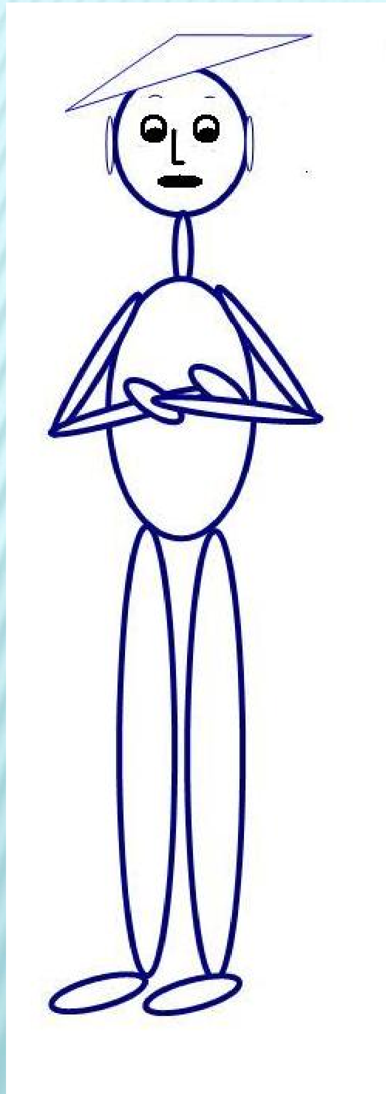
Antineutrino detection with no directional sensitivity

- Detection method is by scintillation detection.
- Gamma rays that produce the scintillation for detection, are generated from the reaction products namely neutron and positron.
- Detection time is in micro seconds.

Antineutrino detection with directional sensitivity

- Detection method is by Cerenkov radiation detection.
- The reaction product, namely, positron itself emits Cerenkov radiation in a characteristic cone shape with a vertex in the direction of the incident antineutrino.
- Detection time is in pico seconds.

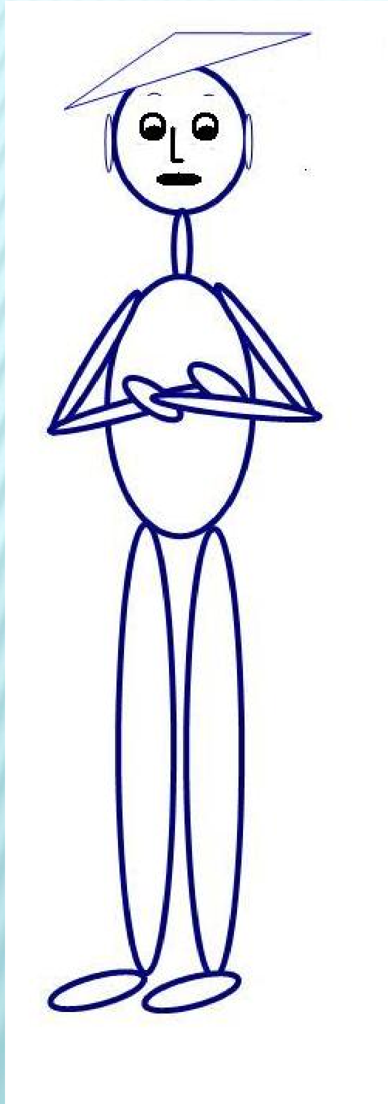
Session Overview



This session provided

- Basics of radiation characteristics of heat producing elements (HPE):
- Alpha, beta, gamma, neutrino and antineutrino radiations
- Alpha, positive beta decay and negative beta decay, neutrino and antineutrino emission in K, U, Th decay.
- Long-lived radiogenic Isotopes of the heat producing elements of K, U and Th, their half-lives, isotopic abundances
- U and Th decay series
- ^{40}K decay scheme.

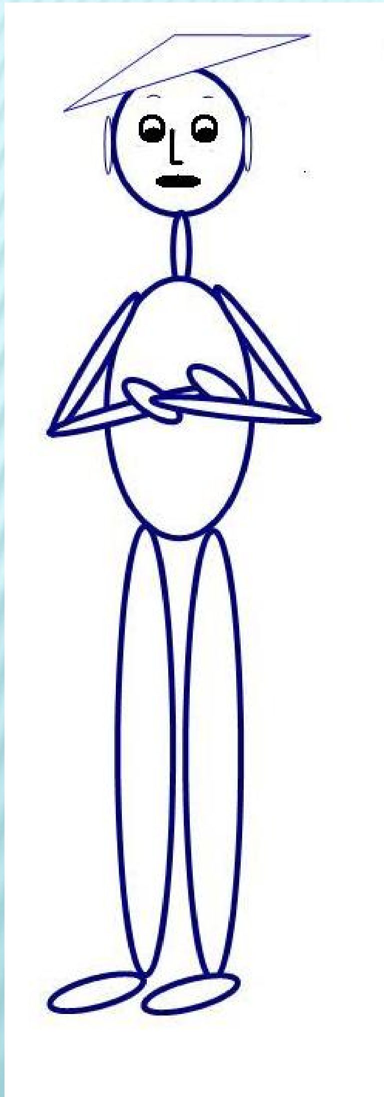
Session 2 Review



Basics of Radiation Detection Concepts:

1. Interaction of radiation with the detection medium
2. Detection signal: Charge collection
3. Detection signal: Charge collection to pulse formation
4. Energy resolution
5. Detection efficiency and solid angle

Session 2 Review



Basics of Antineutrino Radiation Detection Concepts:

1. Antineutrinos as probes to study Heat Producing Elements (HPE) in the deep interior of the Earth:
2. Antineutrino detection by using inverse beta decay reaction products
3. Inverse beta decay nuclear reactions for antineutrinos detection
4. Basic components of an antineutrino detector
5. Background Interferences
6. Antineutrino detection without directional sensitivity by scintillation detection

Session 2: Student Assignments January 19, 2010

1.

Read:

Uranium and Thorium decay series.

Chapter 16.2 Genealogy of nuclides which emit α rays, p. 517-523.

The atomic nucleus,

R. D. Evans

http://www.archive.org/details/atomicnucleus032805mbp.pdf

Write:

For the U and Th decay series, provide the half-lives of all the decay products, identifying the type of decay and the energies of predominant alpha and beta rays.

Provide your understanding of the decay series.

Session 2: Student Assignments
January 19, 2010

2.

Read:

i) Reines, F., and C. L. Cowan, Jr.,

Detection of the Free Neutrino.

Physical Review Letters, 1953, 92: 330.

ii) Reines, F., C. L. Cowan, Jr., F. B. Harrison,

A. D. McGuire, and H. W. Kruse.,

Physical Review, 1960, 117 (1) : 159-174.

Detection of the Free Neutrino – Reines and Cowan Experiment

http://library.lanl.gov/cgi-bin/getfile?00326606.pdf

Write:

Summarize your understanding in your own words.

The write up should be at least 1.5 to 2 full pages.

Session 2: Student Assignments
January 19, 2010

3.

How are antineutrinos detected?

How is their presence confirmed?

What is the importance of detection threshold energy?

How is antineutrino detection important to the analysis of HPE in the Earth?

References

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  Physical Review, 1960, 117 (1): 159-174.

- The Reines and Cowan Experiments
  http://library.lanl.gov/cgibin/getfile?00326606.pdf

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  Cambridge, MA, USA
- The NORM Group Organization,
  Cambridge, USA and Guelph, Canada

is acknowledged.

END of SECOND SESSION

12.091 Basics of Analysis with Antineutrinos from Heat Producing Elements – K, U, Th in the Earth
January (IAP) 2010