

**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 5: January 22, 2010, 2 PM to 4 PM*

**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**

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**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,  
 $^{40}\text{K}$  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**

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**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

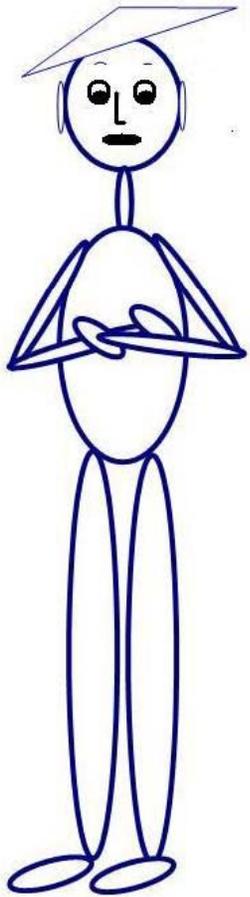
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The course work involves the following:

- |                                              |            |
|----------------------------------------------|------------|
| <b>1. Class attendance and participation</b> | <b>25%</b> |
| <b>2. Reading assignments</b>                | <b>25%</b> |
| <b>3. Homework assignments</b>               | <b>15%</b> |
| <b>4. Student report</b>                     | <b>15%</b> |
| <b>5. Student presentation</b>               | <b>15%</b> |

Required percentage to pass this course is 95%.

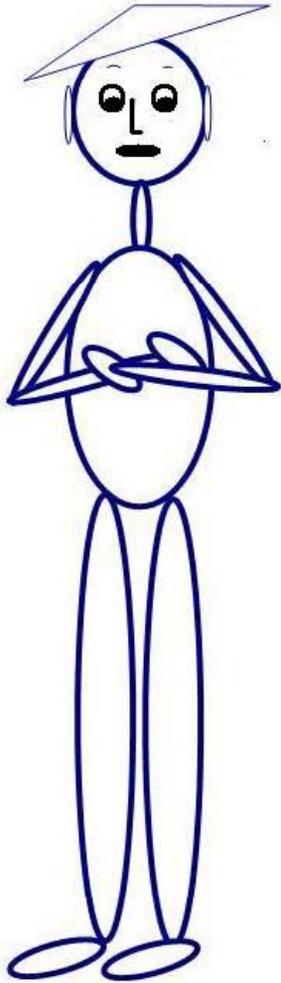
# Course Overview



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

# Session 5 Objectives

## January 22, 2010



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

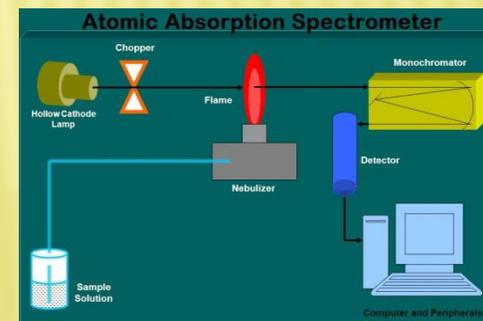
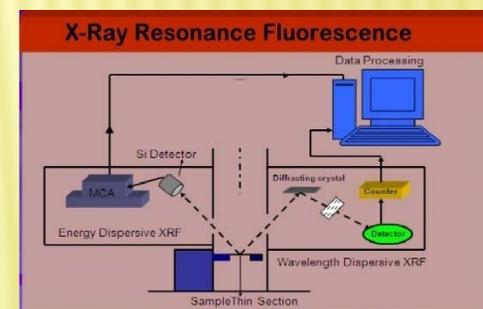
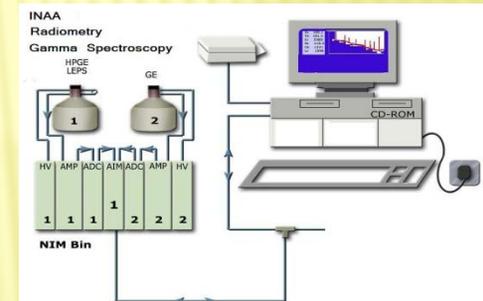
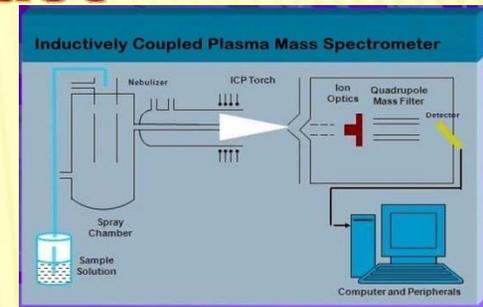
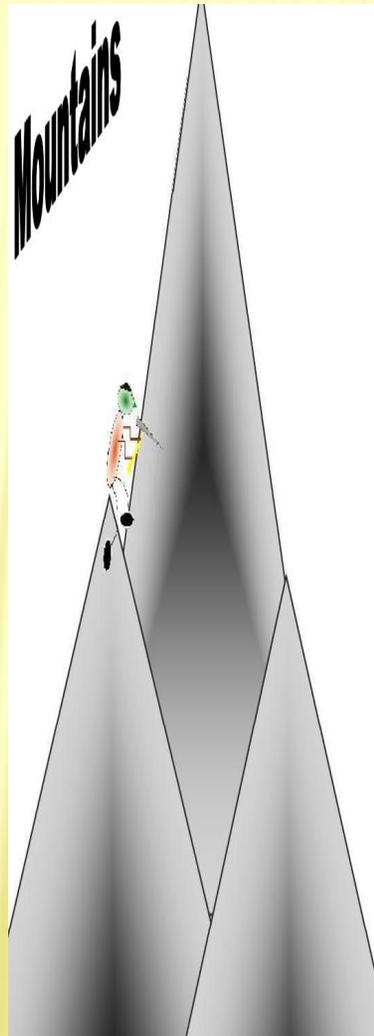
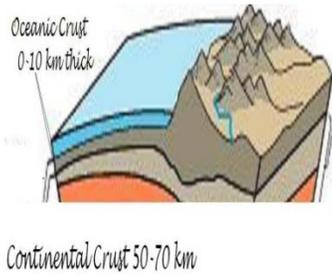
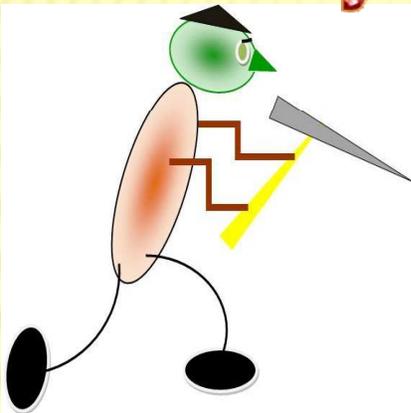
# Assaying of Heat Producing Elements (HPE)

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**Nuclear analytical techniques for geochemical investigations:**

- ✘ Radiometric and X-ray techniques evolved rapidly with developments in instrumental analysis by exploiting the signals generated by characteristic alpha, beta, gamma and x-rays from the Heat Producing Elements (HPE) namely K, U, Th.**
- ✘ High resolution and high sensitivity radiation detectors are developed such as solid state detectors.**

# Conventional field sampling of crust Geophysical and Geochemical HPE analyses



**Field sampling**  
- Climbing mountains

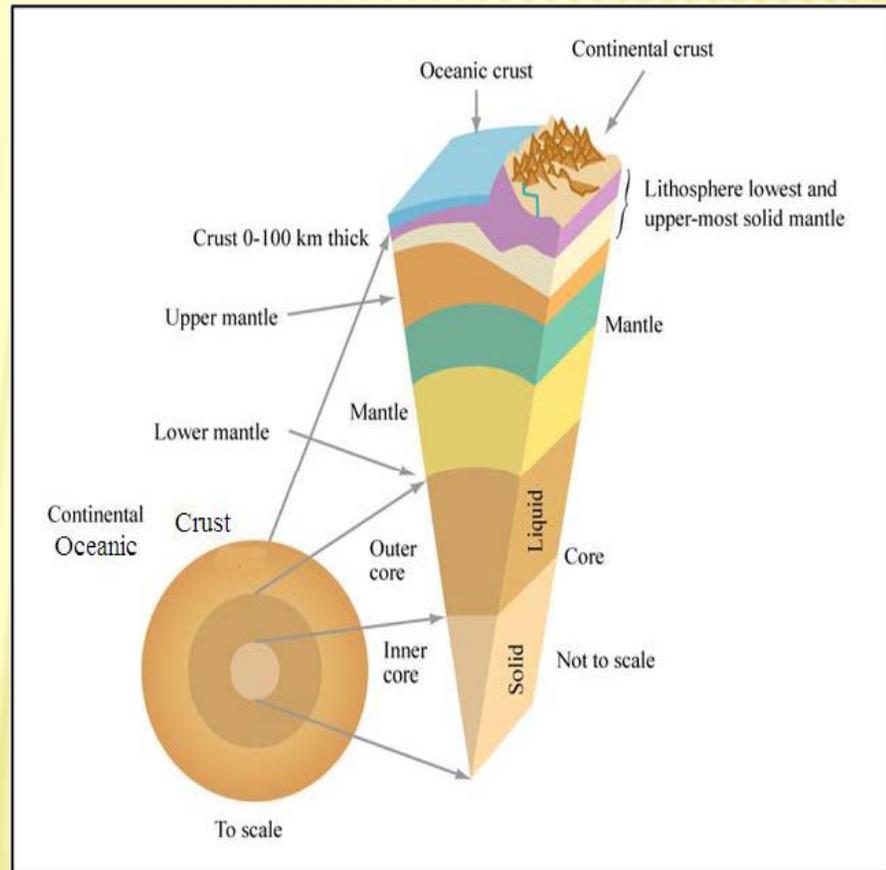
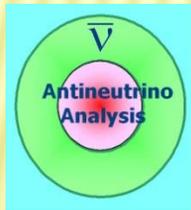
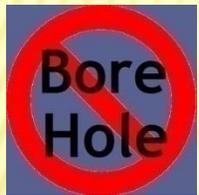
- Using Bore hole logging techniques

**Ocean floor sampling**  
using Submersibles & research ships

## **Limitations of the geochemical assay techniques and sampling**

- ✘ Insufficient penetrating power of the radiation used in the assay technique for in-situ assaying in the field, or in the context of assaying the whole Earth. In-situ sampling is needed to reduce the cost of field sampling.**
- ✘ Necessity for in-situ sampling at ever increasing depths to investigate the deep interior regions of the Earth.**

# Analytical techniques for Probing the Earth's deep interior for HPE



# **Antineutrinos for assaying the HPE of the Earth**

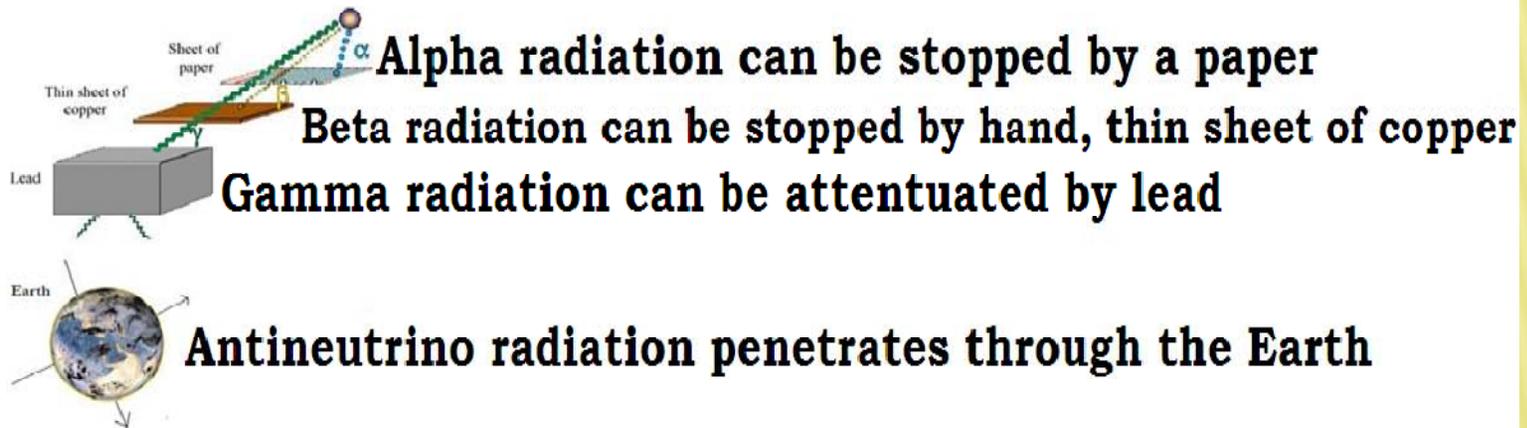
- × Neutrinos and antineutrinos are emitted in nuclear beta decay.**
- × The antineutrinos emitted from the negative beta decay of the radioisotopes of K, U and Th can be used ideally for assaying these elements in the deep interior regions of the Earth, because of the penetrating power of the antineutrinos.**

# **Antineutrinos for assaying the HPE of the Earth**

- × Penetrating power and directionality:**
- × Compared to the  $\alpha$ -,  $\beta$ -,  $\gamma$ - and x-rays emitted in the radioactive decay of unstable elements, antineutrinos/neutrinos are weakly interacting particles.**
- × Not stopped or scattered from their initial direction of travel or, their intensity attenuated by absorbers or shielding materials commonly used to stop the other radiations.**

# Antineutrinos for assaying the HPE of the Earth

## Antineutrinos - a probing tool



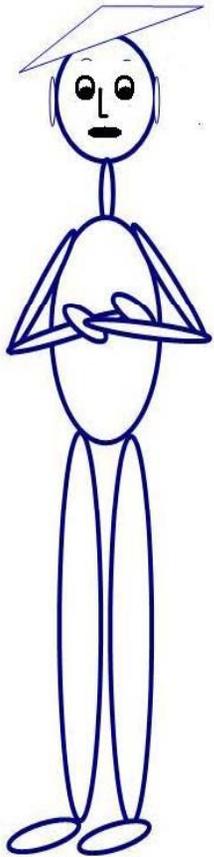
**Antineutrinos are the radiation of choice for probing the radioactivity in the deep interior of the Earth, because of their penetrating power.**

**Figure. Relative advantage of using antineutrinos as a radiation probe in radiometric techniques for the assay of the heat producing elements (HPE).**

# **Antineutrinos for assaying the HPE of the Earth**

- ✘ Not stopped or scattered from their initial direction of travel or, their intensity attenuated by absorbers or shielding materials commonly used to stop the other radiations.**
- ✘ Neutrinos travel in straight lines from the point of origin to the point of detection. This characteristic is advantageous for bulk in-situ assay in the field or, for whole Earth assay and for tomography of the radioactivity in the Earth.**

# Next proceeding to



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

# **I. General Considerations**

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## **1. Corroborating and improving the precision of the HPE assays already done:**

**This requires detectors of high sensitivity with spectroscopic capability for doing in-situ assays of HPE.**

## **2. Assaying the total radioactivity in the Earth including the core without regard to individual HPE:**

**In contrast to the above consideration, another consideration to be taken into account is assaying the total radioactivity in the Earth including the core without regard to individual HPE. In this case the spectroscopic capability is not required and, a detector with lower detection sensitivity may be acceptable.**

# **I. General Considerations**

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## **3. Understanding the discrepancies in heat flow calculations:**

**Another consideration is identifying the concentrations of HPE in the interior regions of the Earth inaccessible by current sampling methods seems in order to understand the discrepancies in heat flow calculations.**

## **4. Overall cost of the optimized detector of choice:**

**The sensitivity and spectroscopic capability requirements determine the overall cost of the optimized detector of choice for the particular application in the research area of interest.**

## **II. Selection Considerations of Antineutrino Detector Types**

**In general, there are two types of antineutrino detectors:**

- 1) With minimal/no directional sensitivity,**
- 2) With full directional sensitivity.**

## **II. Selection Considerations of Antineutrino Detector Types**

### **1) With minimal/no directional sensitivity:**

- ✘ The scintillation detectors based on the principle of inverse beta decay for the detection of antineutrinos are only capable of giving the average concentrations of the HPE in the whole Earth provided they have the minimum detection sensitivity for the particular application.**
- ✘ Because of their lack of full directional sensitivity they cannot localize precisely where the activity originates from the HPE of interest.**

## **II. Selection Considerations of Antineutrino Detector Types**

### **2) With full directional sensitivity:**

- ✘ If localizing the HPE radioactivity is a consideration when selecting a detector with a particular lower limit of detection sensitivity, then the type of antineutrino detector that will meet this requirement needs to be taken into account.**

## **II. Selection Considerations of Antineutrino Detector Types**

**Practical detectors designed and built with directional sensitivity:**

- ✘ They are a class of scintillation detectors known as Cérenkov detectors.**
- ✘ They have been used primarily for studies of energy production in the Sun and astrophysical phenomena such as Super Novae.**

## **II. Selection Considerations of Antineutrino Detector Types**

- ✘ Cérenkov detectors suffer from limited detection sensitivity for HPE determination at this time.**
- ✘ They can be optimized to improve the detection sensitivity.**
- ✘ Together with spectroscopic capability to identify the concentrations of the individual HPE in the different regions of the Earth the Cérenkov detectors are the most expensive and time consuming antineutrino detectors to build and operate.**

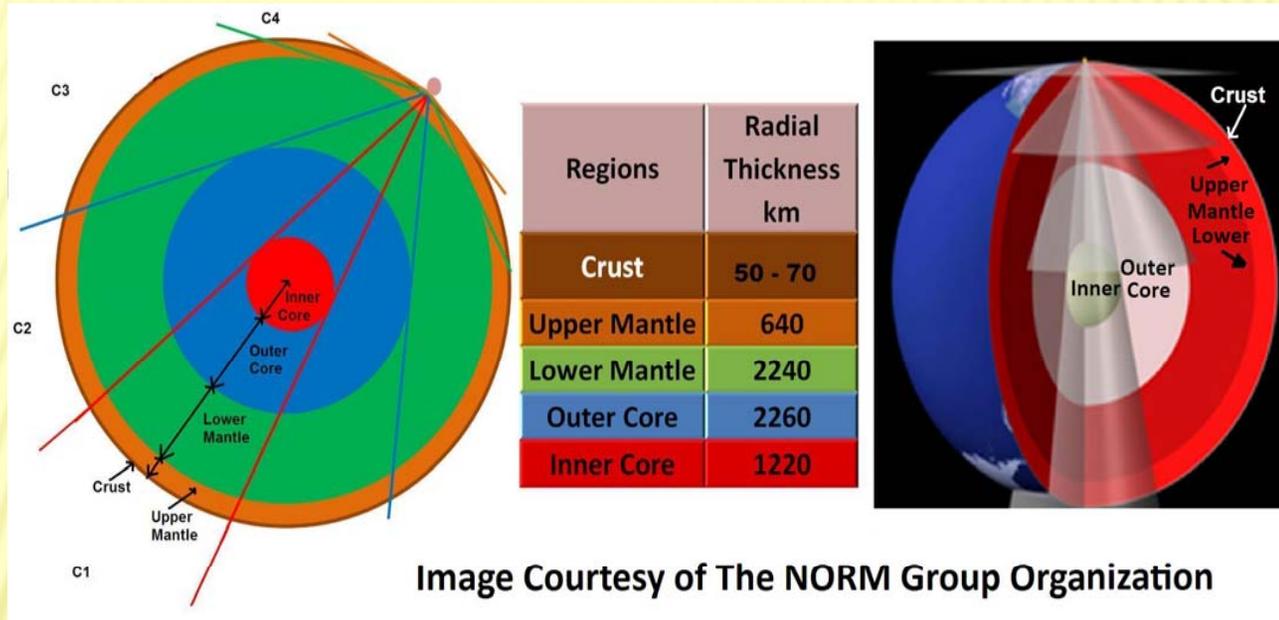
## **II. Selection Considerations of Antineutrino Detector Types**

- ✘ Cérenkov detectors require deep underground locations to minimize the cosmic-ray component of the background while maximizing the signal to background ratio in the detection of the signals from the HPE in the Earth.**

# III. Tomographic Considerations

- ✘ **The total radioactivity due to K, U, Th from the Earth, and the activities from the individual regions of the Earth, especially from the upper and lower mantle, outer and inner core regions are not determined by direct experimental methods so far.**
- ✘ **Determination of abundances of K, U, TH from different regions of the Earth should be geochemical model independent.**

# III. Tomographic Considerations

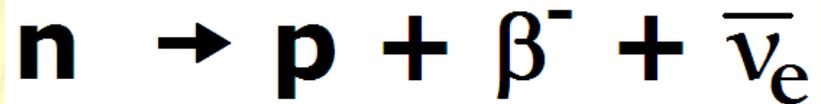


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**In order to locate precisely the origin of the antineutrinos from each region of the Earth at least 5 or more independent tomographic determinations are required, together with the solid angles of detection aligned properly for each region of interest.**

## IV. Spectroscopic Considerations

- ✘ A neutron in an unstable nucleus becomes a proton emitting an electron and an antineutrino.



- ✘ The spectrum of energies extends from zero to a maximum energy characteristic of the radioactive decay.
- ✘ For example, elemental potassium consists of three isotopes of which  $^{40}\text{K}$  is radioactively unstable and decays with a half-life of 1.28 billion years.
- ✘ Both antineutrinos and neutrinos are emitted in the negative and positive beta decay of  $^{40}\text{K}$  in the proportions of 89.3 % and 10.7 % respectively, and are not mono-energetic.

## **IV. Spectroscopic Considerations**

- × Energies of antineutrinos originating from K are less than the range of energies of antineutrinos from thorium and uranium.**
- × This difference in the antineutrino spectra has to be taken into account when considering the detection of HPE by instrumental techniques.**
- × Energy distributions in the antineutrino spectra of all the important heat producing elements in the Earth are shown in figure. The antineutrino intensity falls off to zero with increasing energy. The vertical dotted line shows the threshold energy for detection by detectors employing inverse beta decay reaction. Antineutrinos occurring in the decay of HPE are confined to energies below 3 MeV.**



## **IV. Spectroscopic Considerations**

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**Therefore, most of the antineutrino intensity arising from the HPE in the Earth, is below the detection threshold of the detectors employing inverse beta decay reaction.**

**In addition, the inverse beta decay reaction cross-section falls off at lower energies than fission neutrino energies limiting the detection sensitivity of these detectors.**

# V. Background Interferences

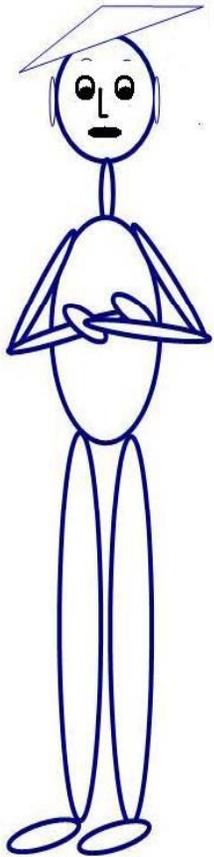
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**There are primarily four component sources in the background spectrum, interfering with the signal of interest:**

- 1. The intrinsic 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 abundances accurately.**

**Next proceeding to**



**Conclusions**

# Conclusions

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**It can be seen from the above considerations that**

- ✘ The characteristics of the antineutrino detector of choice determine the end result of the measurement of K, U, Th abundances.**
- ✘ An antineutrino detector without tomographic capability cannot provide independent measurements of the HPE separately in each individual region of the deep interior of the Earth all the way to the core.**

# Conclusions

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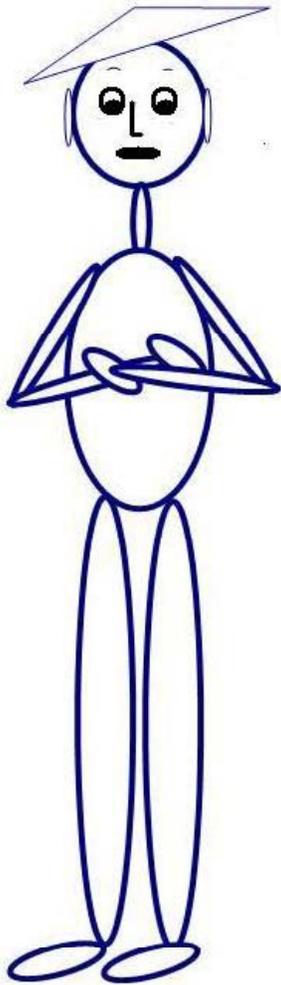
- ✘ Tomographic and spectroscopic detector requires careful consideration regarding detection sensitivity and energy resolution.**
- ✘ Experience shows that such large sophisticated detectors may take up to ten years to secure the needed funding and manpower, and another five years to construct and commission them. Only then can any data be expected from the dedicated detectors for analysis of HPE in the deep interior regions of the Earth.**

# Conclusions

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- ✘ **Cost and time considerations are of paramount importance in the research area of interest.**
- ✘ **It is logical and important to start immediately with a mobile detector to investigate more thoroughly the background components of the antineutrino detection measurements.**
- ✘ **The advantage of low cost and short time for deployment of a  $1 \text{ m}^3$  detector can be exploited depending on the total radioactivity in the Earth.**

# Session Overview



- ✦ **Considerations for a dedicated antineutrino detector for analysis of K, U, Th in the deep interior regions of the Earth:**
  - 1. General considerations**
  - 2. Selection considerations for antineutrino detector types**
  - 3. Tomography considerations**
  - 4. Spectroscopic considerations**
  - 5. Background interferences.**
- ✦ **Summary of conclusions.**

# References

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- ✘ **Considerations for a dedicated geoneutrino detector for geosciences**

**P. Ila, W. Gosnold, G. Lykken, P. Jagam**

**<http://arxiv.org/ftp/arxiv/papers/0902/0902.3607.pdf>**

**Presented in AGU Special Session:**

**Terrestrial Heat Flux and Geoneutrinos: Estimating the Earth's Heat Flux**

**AGU Fall Meeting, December 15 – 19, 2008, San Francisco, CA, USA**

**EOS Trans. AGU, 2008, 89(53), Fall meeting, Suppl., Abstract T21C-1978.**

## References

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- ✘ **Potential and Limitations of Geoneutrino Detection Technique for Studying Heat Producing Elements in Earth's Deep Interior, P. Jagam, The NORM Group, Canada, Invited Talk , AGU 2009 Joint Assembly, The Meeting of the Americas, 24–27 May 2009, Toronto, Ontario, Canada  
Paper: U24A-04, AGU 2009 Joint Assembly, The Meeting of the Americas 24–27 May 2009, Toronto, Ontario, Canada.  
Eos Trans. AGU, 90(22), Jt. Assem. Suppl., Abstract U24A-04.**

# Acknowledgements

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