Subatomic Physics II

Problem Set 10

Due on December 16, 2021, 11:59 PM

Problem 10: Geoneutrinos

Decay of radioactive elements such as ^{238}U and ^{232}Th inside the Earth is a source of terrestrial heat (radiogenic heat) and also of neutrinos, which are called *geoneutrinos*. Although the total heat production inside Earth is known (47 ± 2 TW), the radiogenic heat is very poorly constrained. According to different models, the radiogenic power can be anything from 3 to 30 TW. Measuring the geoneutrino flux will hugely improve this estimate.

Let us estimate whether such a measurement is feasible.

- Assume that the antineutrino is detected by the inverse β-decay $\bar{\nu}_e p \to e^+ n$ it induces in the detector. Calculate the neutrino energy threshold E_0 in MeV. (1pt)

- The uranium decay chain $^{238}\text{U} \to {}^{206}\text{Pb}$ is an important source of radiogenic heat and geoneutrinos. This decay releases 52 MeV of energy per ^{238}U nucleus and produces a number of antineutrinos (how many?). On average one of these $\bar{\nu}_e$ has an energy above the threshold E_0. Assuming that uranium decays are responsible for 8 TW of radiogenic heat, calculate the geoneutrino flux f (measured in cm^{-2}s^{-1}) through the Earth's surface. Assume for simplicity that uranium is homogeneously distributed inside the Earth. (2pt)

- Neutrinos oscillate on their way from the Earth's interior to the detector. The probability that, after travelling a distance L, a $\bar{\nu}_e$ remains $\bar{\nu}_e$, is given by

$$P_{ee} = \sin^4\theta_{13} + \cos^4\theta_{13}\left[1 - \sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)\right],$$

  where θ_{12}, θ_{13} and Δm_{21}^2 are the neutrino oscillation parameters. Calculate the oscillation length for a 2.2 MeV neutrino. Comparing it with the Earth's radius, deduce the *average* survival probability $\langle P_{ee}\rangle$ for geoneutrinos to reach the detector on the surface in the $\bar{\nu}_e$ state. (2pt)

- The cross section of the process $\bar{\nu}_e p \to e^+ n$ is given by the formula

$$\sigma = \frac{G_F^2}{\pi}(g_V^2 + 3g_A^2)(E_\nu - \Delta)\sqrt{(E_\nu - \Delta)^2 - m_e^2} \;,$$

  where G_F is the Fermi constant, $g_V = 1, g_A \approx 1.23$ are the vector and axial coupling constants, and $\Delta = m_n - m_p$. For an average geoneutrino energy $E_\nu = 2.2$ MeV, calculate σ in cm^2. (1pt)

- Consider a neutrino detector filled with 1000 tons of water. Using the above results and assuming 100% detection efficiency, estimate the number of detected geoneutrino events per year. (2pt)

- It is known that the Sun produces a huge neutrino flux, of the order of 10^{10} cm^{-2}s^{-1} at the surface of the Earth, in the same energy range. Why is it nevertheless possible to measure geoneutrinos despite such a huge solar background? What do you think is another important source of background, and how can one control this? (2pt)