Homework Solutions

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Homework Problem 1

- How many antineutrinos are produced per second for a typical 3-gigawatt (thermal) commercial reactor?

1. Each fission releases ~200 MeV energy. How many fissions are produced per second?

   3e9 / (200e6 * 1.6e-19) = 1e20 fissions/sec

2. Each fission produce ~6 antineutrinos on average from the beta-decay chains. How many antineutrinos are produced per second?

   1e20 fissions/sec * 6 = 6e20 antineutrinos/sec

Homework Problem 2

- Daya Bay's antineutrino detector (AD) is a 20-ton liquid scintillator detector. The far ADs are placed at ~1.6 km away from reactors with a total power of ~17 GW. How many inverse beta decay(IBD) reactions are expected per day in each far AD?

  1. The hydrogen mass fraction in the AD is ~12%. How many free protons (from hydrogen) are there in each AD?

  20e6 * 0.12 / 1 * 6e23 = 1.4e30 protons

  (hydrogen mass: 1 g/mol; Avogadro number: 6e23 /mol)

Homework Problem 2

- Daya Bay's antineutrino detector (AD) is a 20-ton liquid scintillator detector. The far ADs are placed at ~1.6 km away from reactors with a total power of ~17 GW. How many inverse beta decay(IBD) reactions are expected per day in each far AD?

  2. How many reactor antineutrinos per cm^2 per second is expected at the AD? (this is referred as the "flux")

  2e20 * 17 / (4 * 3.14 * 1.6e5 * 1.6e5) = 1e10 antineutrinos / sec / cm^2

  (From problem 1 we know reactors produce 2e20 antineutrinos/sec/GW)

Homework Problem 2

- Daya Bay's antineutrino detector (AD) is a 20-ton liquid scintillator detector. The far ADs are placed at ~1.6 km away from reactors with a total power of ~17 GW. How many inverse beta decay(IBD) events are expected per day in each far AD?

  3. The average IBD cross section is ~3×10^{-43} cm^2 , calculate "event rate = flux * cross section * protons", assuming 100% detection efficiency. (remember that only 1/3 of all reactor antineutrinos can do IBD)

  1e10 * 3e-43 * 1.4e30 / 3 * 86400 = 120 events/day

  (1/3 of antineutrinos can do IBD; 1 day = 86400 sec;)

Homework Problem 3

- Can you find the antineutrino disappearance from the given information?
  1. Plot the measured antineutrino signal rate of each AD vs. the expected flux, assuming each AD has the same size, and each reactor has the same power.
  2. Fit the data (what function to use?) with the near ADs and extrapolate to the far ADs. What do you see?
  3. What is the "survival probability" in the far ADs relative to the near ADs? What is the statistical significance of this observation?
  4. What is the size of θ_{13} using the oscillation formula?

$$P = 1 - \sin^2 2\theta_{13} \cdot sin^2(1.27|\Delta m^2_{ee}(eV^2)| \cdot \frac{L\ (m)}{E(MeV)})$$

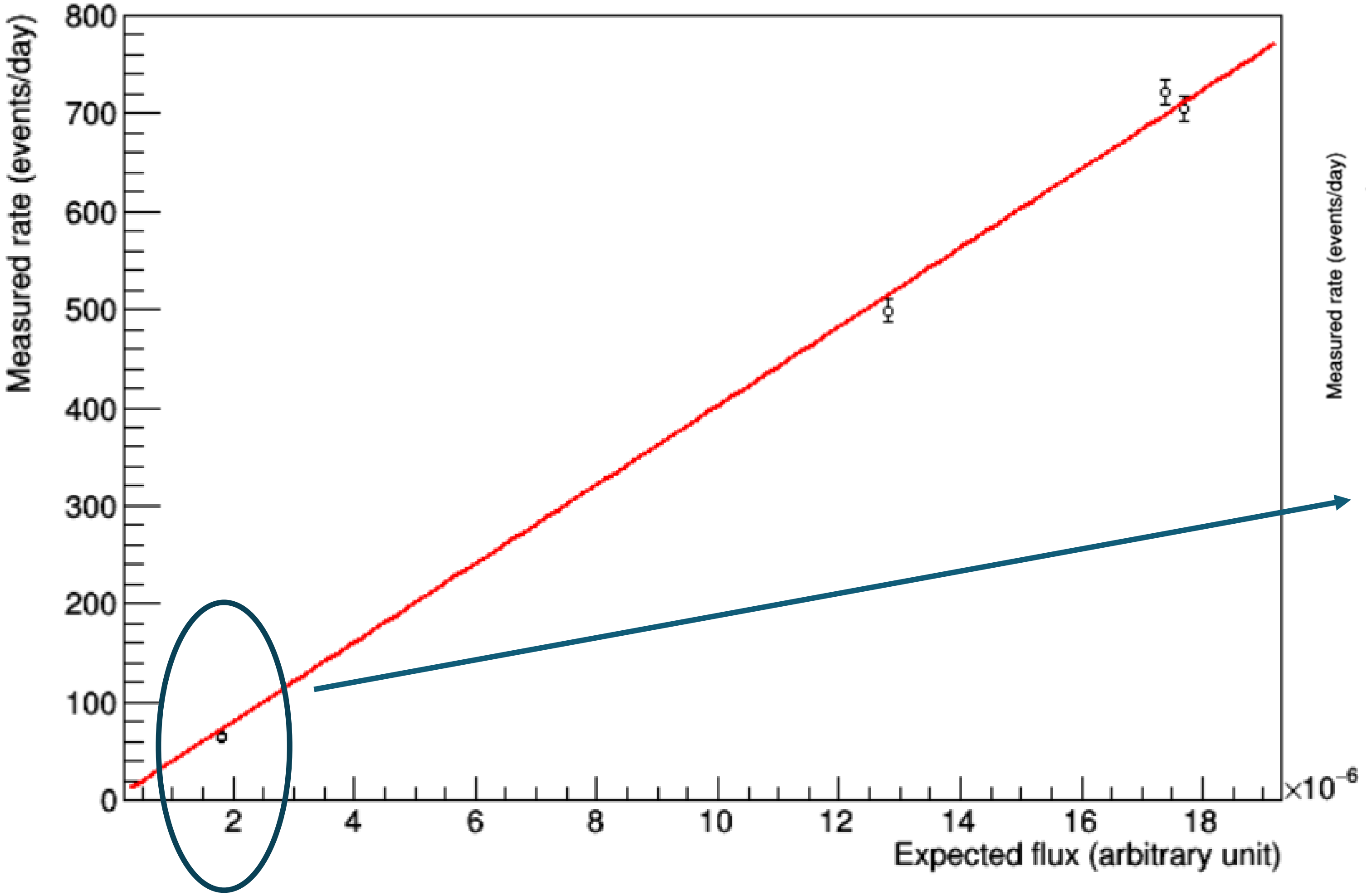
Δm^2	2.4×10^{-3} (eV^2)
L	1.66×10^{3} (m)
E	3.5 (MeV)

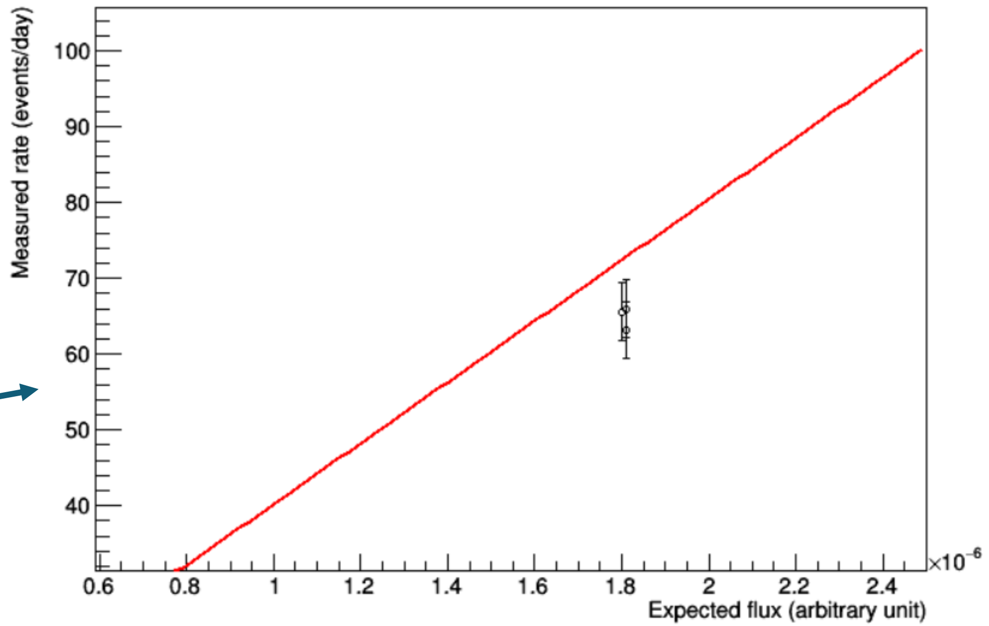
Homework Problem 3

- The solution is in the ROOT script “theta13.C”
  - Run: `root -l theta13.C`
  - See the in-line comments in the script to understand

1. Plot the measured antineutrino signal rate of each AD vs. the expected flux, assuming each AD has the same size, and each reactor has the same power.
2. Fit the data (what function to use?) with the near ADs and extrapolate to the far ADs. What do you see?

After correcting for the $1/L^2$ inverse power law, we should expect a linear relationship

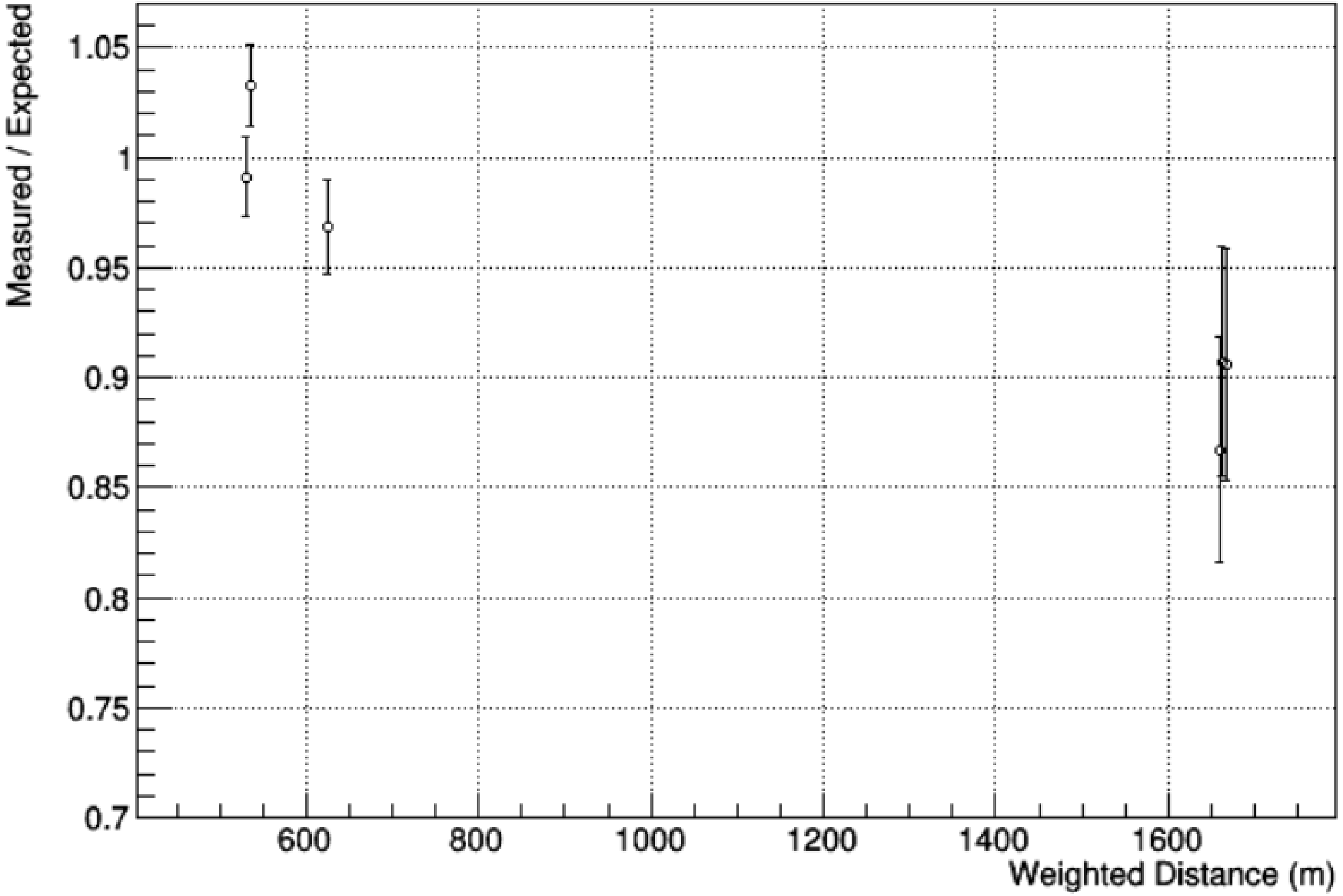




The "disappearance" of events at the far ADs should be clear when extrapolating from the near ADs

3. What is the “survival probability” in the far ADs relative to the near ADs? What is the statistical significance of this observation?

We can replot the data over the expected rate from the fit vs. distance to make the disappearance clearer.



- Average over the 3 detector in EH3, the ratio at fall hall (survival probability) is 0.89 +- 0.03
  - The “disappearance probability” is 0.11 +- 0.03
  - a 3σ measurement of the electron antineutrino disappearance in 5 days

4. What is the size of θ_{13} using the oscillation formula?

$$P = 1 - \sin^2 2\theta_{13} \cdot sin^2(1.27|\Delta m^2_{ee}(eV^2)| \cdot \frac{L\ (m)}{E(MeV)})$$

Δm^2	2.4×10^{-3} (eV^2)
L	1.66×10^3 (m)
E	3.5 (MeV)
P	0.894
$\sin^2 2\theta$	0.108 +- 0.030

The precisely measured $\sin^2 2\theta$ today is 0.0856 ± 0.0029

Caveats in this simplified analysis

- We assumed no oscillation in the near sites so that we can use EH1 and EH2 to predict EH3
  - In reality, the θ_{13} fit should also consider the small disappearance at the near site (~2%)
- We assumed equal power for each reactor, which is a good assumption in a short time scale
  - In reality, we have the time dependent power and fission fraction information of each reactor from the nuclear power plant.
- We did not consider various systematic uncertainties as the statistical uncertainty dominates the measurement for the 5 days
- Nevertheless, this exercise shows how physicists can use basic knowledge to simplify a problem and get a correct answer without complicated mathematics. This is an important skill to develop as a good researcher.