

## Week 5

April 28, 2018

# Gone Fission! Neutrinos From Nuclear Reactors

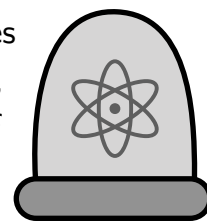


Nuclear reactors produce huge numbers of electron-type antineutrinos. Indeed, it was an experiment based at a reactor that first discovered neutrinos in 1956! Power plant reactors provide a well-known source of neutrinos which can be used to study flavor-changing oscillation phenomena in detail. Meanwhile, since neutrinos penetrate all sorts of matter and are thus impossible to block, they provide an opportunity to monitor nuclear reactor operation. Beyond the reactors we build, natural caches of fissile material within the Earth produce so-called geoneutrinos, and studying these can provide a unique window to measure our own planet's internal composition.

*This week, we will discuss neutrinos from nuclear reactors from three different perspectives: measurements of neutrino properties, studies of the Earth's composition, and monitoring of nuclear reactors.*

## I. Reactor Antineutrinos

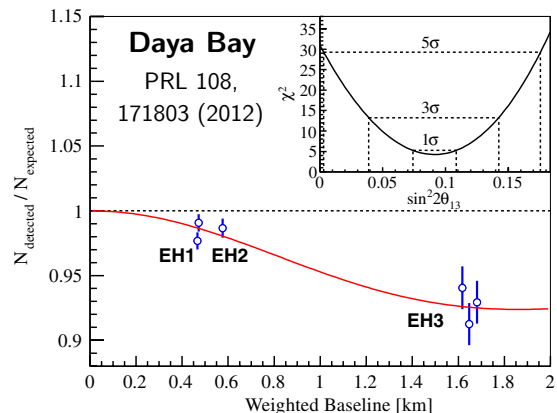
Nuclear power reactors operate by extracting the heat generated in carefully-controlled nuclear fission chain reactions. These processes create an array of unstable isotopes that undergo nuclear beta decay, emitting large numbers of electron-type antineutrinos with energies of a few MeV. These can then be measured through an inverse beta decay interaction (which produces a positron and a neutron) in a nearby neutrino detector.



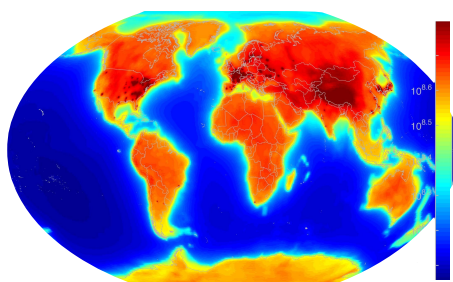
*Neutrino Oscillations:* The types of neutrinos produced in weak interactions — "flavor states"  $\nu_e$ ,  $\nu_\mu$ , and  $\nu_\tau$  — are different from the neutrinos that propagate through space, the "mass states"  $\nu_1$ ,  $\nu_2$ , and  $\nu_3$ . The flavor states are quantum superpositions of the mass states, and interferences between the latter lead to an apparent change in the neutrino flavor over time: you can produce a  $\nu_e$ , and later there is a probability to measure it as a  $\nu_\mu$ , for example. Reactors provide a source of electron-type antineutrinos with a well-known location and energy distribution, allowing us to make precision studies of these neutrino flavor changes ("oscillations").

*The Race to  $\theta_{13}$ :* Following the solar and atmospheric neutrino oscillation measurements, one parameter in the model remained unknown. Theoretical models predicted this would be possible, but difficult, to measure using reactor antineutrinos.

Three precision experiments were devised to pursue it: Double Chooz (France), RENO (South Korea), and Daya Bay (China). In a surprise announcement in 2012, Daya Bay presented the first measurement of this parameter, which turned out to be larger (and thus easier to measure) than expected. This parameter is of special importance, because a large value makes it practical to study possible differences between neutrinos and antineutrinos in neutrino oscillation experiments.



## II. Geoneutrinos



**Antineutrino Flux Map**

Scientific Reports 5:13945 (2015)

Several competing models provide descriptions of the Earth's composition, all consistent with the internal heat production we observe on the surface. It is believed that the Earth's heat is a combination of "primordial" heat left over from the planet's formation and heat continuously generated by naturally-occurring nuclear reactors (deposits of fissile materials in the crust and mantle). Measurements of the antineutrinos produced in these "reactors," the so-called geoneutrinos, can help resolve the ambiguity and improve our understanding of our planet.

## III. Reactor Monitoring

Neutrinos can travel through vast amounts of matter, so it is impossible to block the neutrinos produced in nuclear reactors. Since fissile material that could be used to construct a nuclear weapon (such as  $^{235}\text{U}$  or  $^{239}\text{Pu}$ ) are generated in nuclear reactions, the production of these materials also creates telltale neutrinos. Large neutrino detectors could therefore be used to monitor nuclear programs, detecting the presence, and potentially the isotope composition, of nuclear reactors. Groups such as WATCHMAN are working to demonstrate the feasibility of this highly relevant practical application of neutrino physics.