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ISSUES AND EVENTS

Reactor experiments seek missing neutrino mixing angle

Exposing the details of how electron neutrinos change flavor could be a step toward determining the neutrino mass hierarchy and explaining the imbalance of matter and antimatter in the universe.

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The race is on to pinpoint θ_{13}, the last unknown mixing angle and a key parameter needed to decode neutrino oscillation. The Double Chooz experiment being constructed in northern France is poised to get results first, while a rival experiment at southern China's Daya Bay will aim for greater sensitivity.

Nuclear Power Plant in France

Nuclear Power Plant in China

Following a long tradition—from the first detection of neutrinos in the 1950s at Savannah River in South Carolina to the ongoing KamLAND experiment in Japan—both the Double Chooz and Daya Bay experiments will monitor antineutrinos emitted from nuclear power reactors. They will watch for the disappearance of electron antineutrinos by comparing the flux and energy spectrum in detectors located far from and close to the reactors. "An effect could be seen independently by these two means," says Double Chooz spokesman Hervé de Kerret of the Astroparticle and Cosmology Laboratory at the University of Paris VII. "If both of them give consistent nonzero results, it would be a smoking gun for the value of θ_{13}."

Rival experiments

In both the Double Chooz and Daya Bay experiments, the distance to the far detector will be a kilometer or so, the length scale for oscillations of electron neutrinos into muon or tau neutrinos; θ_{13} is a parameter of the probability distribution for such oscillations. KamLAND, by contrast, watches for different oscillations, at 150 to 200 km.

The best measurement to date was made at Chooz, Double Chooz's predecessor, and sets the upper limit of $\sin^2 2\theta_{13}$ at about 0.2. Double Chooz aims to explore down to 0.03, while the planned sensitivity for the Daya Bay experiment is 0.01.

The detectors at both sites consist of nested cylinders, with gadolinium-doped liquid scintillator at the core, then a layer of undoped scintillator, all surrounded by mineral oil for shielding. Photomultiplier tubes are embedded in the oil. When an incident antineutrino hits a proton in the scintillator, a positron and neutron result. A flash is detected when the positron annihilates, and a second flash occurs when the neutron is captured by a gadolinium nucleus.

Double Chooz's two detectors will catch antineutrinos from two neighboring reactors. To shield the experiment from cosmic rays, the detectors will be housed underground. The construction cost is an estimated €14 million ($17.5 million). France is paying for local civil work and about a quarter of the detectors. Also contributing are Germany, Japan, the UK, Brazil, Russia, and—if the Department of Energy (DOE) and NSF come up with about $3.5 million—the US. The other partners "will build the experiment without us if we are not funded for detector construction," says Double Chooz US co-spokesman Robert Svoboda of the University of California, Davis, and Lawrence Livermore National Laboratory.

At Daya Bay, eight detectors will monitor antineutrinos from six reactors. The detectors will go in tunnels excavated into a mountain. The working assumption is that China will pay for the local infrastructure and split the cost of the detectors with the US, with smaller contributions from the other Daya Bay partners—Hong Kong, Taiwan, Russia, and the Czech Republic. The US share would be in the range of $25 million to $35 million, says US project manager William Edwards of Lawrence Berkeley National Laboratory. The project has to pass several reviews within DOE before US participation is finalized, but Robin Staffin, the associate director for high-energy physics in the agency's Office of Science, says, "We are gearing up to be a full partner in the design, construction, and operation of the Daya Bay experiment."

Building confidence

Double Chooz and the Daya Bay experiment both gain in sensitivity by using detectors near to and far from the source. "If you put a detector close up, you can measure the interaction rate before the neutrinos have had time to mix," says Svoboda. "That does away with the errors in the cross section and the conversion of reactor power to neutrinos. You are left with the error in the efficiency of your detector." That detector error is where Daya Bay could get part of its advantage: The detectors will be movable, and the plan is to swap their positions. "This will eliminate systematic errors in the detectors," says project co-spokesman Yifang Wang of the Institute of High Energy Physics in Beijing. The Daya Bay experiment is also deeper underground and has a larger detector volume and more total power—and more antineutrinos—from its source reactors.

What Double Chooz lacks in sensitivity, it hopes to more than make up for in speed. The experiment is slated to be up and running in late 2008; Daya Bay would follow a year or so later, and both would take data for about three years. "If [Double Chooz] measures a finite value for $\boldsymbol{\theta}_{13}$ first, then it does steal some thunder," says Brookhaven National Laboratory's Laurence Littenberg, a physicist on the Daya Bay experiment. But, he adds, "it's possible that we can be on the same time scale to get to the same sensitivity. They have to do a certain amount of civil construction, too, and the Chinese are very fast."

If $\sin^2 2\boldsymbol{\theta}_{13}$ turns out to be smaller than 0.03, then Daya Bay's greater sensitivity could trump. The measurement is tricky, "so if different instruments at different locations get the same answer, that would be perfect. It would build our confidence," says UC Berkeley's Kam-Biu Luk, co-spokesman for the Daya Bay experiment.

Other experiments in the same vein as Double Chooz and Daya Bay have also been considered in Brazil, Japan, and the US. Still early in the planning stages, an experiment at Angra dos Reis in Brazil would aim to push the sensitivity to below the Daya Bay limit. As a side project, the Angra detector might be used to develop a means to monitor nuclear reactors, says David Reyna of Argonne National Laboratory (ANL), who is involved in both Double Chooz and Angra. "The [energy] spectrum can tell you the ratio of uranium to plutonium in the reactor fuel."

Japan's KASKA, which would have aimed for a sensitivity down to 0.015, was denied funding in September, and the project's researchers have joined Double Chooz.

And an experiment using the Braidwood nuclear reactor in Illinois as its antineutrino source was scrapped last spring, when DOE put its weight behind Daya Bay. "Cost was a big driver," says the agency's Staffin. "We are trying to get the most for our precious funds." Several scientists suggest that pressure from high up in the US government to collaborate with China, and a bad public image of Braidwood in the wake of a tritium leak last year, also played a role in DOE's going with Daya Bay.

Small angle, big implications

The immediate goal of the reactor neutrino experiments is to home in on $\boldsymbol{\theta}_{13}$. The measurement also bears on the broader questions of neutrino mass hierarchy and *CP* violation. Says de Kerret, "The mixing between three kinds of neutrinos has three parameters. The two angles that have been measured are big, and the third is very small. This is a big surprise, because with quarks the corresponding angles are all small. Nobody understands this difference." The big angles correspond to strong mixing and hint that *CP* violation by neutrinos might explain the universe's imbalance of matter and antimatter.

"If you measure a nonzero $\boldsymbol{\theta}_{13}$, it will tell you something about all of these things, but then you have to sort it out," says ANL's Maury Goodman, US co-spokesman for Double Chooz. A measurable $\boldsymbol{\theta}_{13}$ could be used to optimize the accelerator experiments in the works, NO$\boldsymbol{\nu}$A in the US and T2K in Japan—which themselves can estimate $\boldsymbol{\theta}_{13}$, but not as cleanly as a reactor experiment—and to lay out the next steps in neutrino research. But if $\boldsymbol{\theta}_{13}$ is ultimately found to be zero, says Luk, "we cannot extract a *CP*-violating phase. In that case, we have to scratch our heads."

Toni Feder

	
Credit: China Guangdong Nuclear Power Group	*Credit: Électricité de France*

Underground experiments will monitor neutrinos from nuclear power plants in China (left) and France (right).

Credit: Électricité de France

Credit: China Guangdong Nuclear Power Group