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Search for eV sterile neutrinos at a nuclear reactor – the Stereo project

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Abstract. The re-analyses of the reference spectra of reactor antineutrinos together with a revised neutrino interaction cross section enlarged the absolute normalization of the predicted neutrino flux. The tension between previous reactor measurements and the new prediction is significant at $2.7\,\sigma$ and is known as "reactor antineutrino anomaly". In combination with other anomalies encountered in neutrino oscillation measurements, this observation revived speculations about the existence of a sterile neutrino in the eV mass range. Mixing of this light sterile neutrino with the active flavours would lead to a modification of the detected antineutrino flux. An oscillation pattern in energy and space could be resolved by a detector at a distance of few meters from a reactor core: the neutrino detector of the Stereo project will be located at about 10 m distance from the ILL research reactor in Grenoble, France. Lengthwise separated in six target cells filled with $2\,\mathrm{m}^3$ Gd-loaded liquid scintillator in total, the experiment will search for a position-dependent distortion in the energy spectrum.

1. Introduction

In nuclear reactors a large number of unstable fission products is produced. These neutron-rich fission fragments subsequently undergo β^- decay, turning reactors into a pure and intense source of electron antineutrinos. In the past few years, revised analyses of the predicted spectra of antineutrinos emitted by nuclear reactors have been performed, leading to an increase in the total expected flux [1, 2]. Compared to the data of 19 short-baseline reactor experiments along with a re-evaluated neutrino interaction cross section, this resulted in a $\sim 6\,\%$ deficit in the observed-to-predicted ratio of antineutrino events. Known as "reactor antineutrino anomaly", the deficit is significant at $2.7\,\sigma$ [3]. Together with other anomalies found in neutrino oscillation experiments, speculations revived about the possible existence of a fourth neutrino eigenstate: The observed deficit in the measured neutrino event rates could be explained by an additional term in the neutrino oscillation formalism with a squared mass splitting of $\Delta m_{\mathrm{new}} \approx 1\,\mathrm{eV}^2$. This extension corresponds to a fourth mass eigenstate in the eV range and implies the presence of a sterile state in the flavour space.

Reactor experiments detect the antineutrinos via the inverse beta decay reaction ($\bar{\nu}_e + p \rightarrow e^+ + n$). This process is only sensitive to the electron flavour at low energies, allowing for pure flavour disappearance measurements. Although not interacting weakly, the existence of a light sterile neutrino can be tested at a nuclear reactor in the mass range favoured by the reactor neutrino anomaly. Owing to the phenomenon of eigenstate mixing in the neutrino sector, a sterile neutrino would participate in flavour oscillations. This would create, in the $\bar{\nu}_e$ disappearance at very short distances to the reactor core, a distinct oscillation signature as a function of baseline

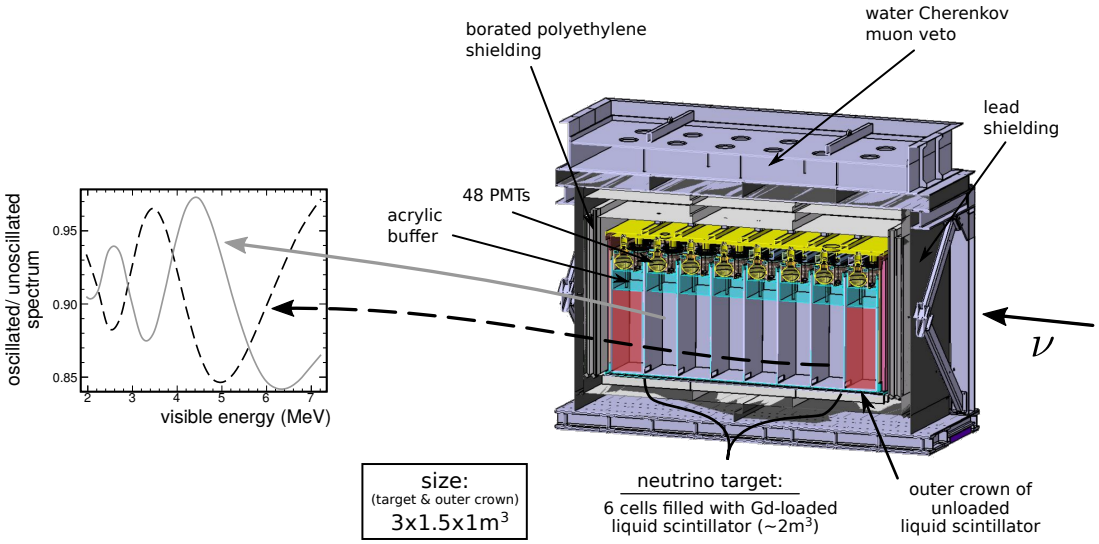

Figure 1. The Stereo detector. The left inset plot sketches the event ratio of the oscillated and unoscillated measured spectrum. The energy dependence of the oscillation pattern changes with distance from the source, as seen for the target cell closest (black dashed line) and furthest (grey solid line) from the core. As oscillation parameters the best fit values of the reactor + gallium anomaly were used [4].

and $\bar{\nu}_e$ energy. An observation of this oscillation pattern would unambiguously prove the sterile neutrino hypothesis right.

2. The Stereo detector and ILL site

The Stereo experiment will measure the neutrino flux emitted by the ILL research reactor (Grenoble, France), which has a nominal thermal power of 58.3 MW. The reactor core is very compact, with 40 cm in diameter and 80 cm in height, which is an important prerequisite to not smear the baseline dependent oscillation. Moreover, its fuel is highly enriched in ^{235}U, which simplifies the computation of the neutrino flux prediction. The neutrino detector (cf. Fig. 1) will be located (9–11) m away from the core and observe about 400 neutrino events per day for a target of 2 m^3 Gd-loaded liquid scintillator. The target consists of six $(38\times90\times90)$ cm^3 sized cells, which are arranged along the reactor-detector baseline. Each target cell is optically separated from the others, allowing to measure the neutrino spectrum for each cell individually which provides a spatial uncertainty of less than 40 cm in the oscillation analysis. The array of target cells is surrounded at its sides by an outer crown volume filled with unloaded scintillator. Its purpose is to enhance the detection efficiency of the gammas produced by the reaction products of the inverse beta decay: the positron annihilation and the neutron capture on gadolinium. The latter releases multiple gammas with a total energy of 8 MeV, well above the energy depositions of natural radioactivity. Both events occur separated by an average time difference of 20 μs, allowing to search for the coincidence and suppress backgrounds. A layer of acrylics and oil separates the liquid scintillators of target and outer crown volume from the 48 PMTs of 8 inch size. About 350 photons will be detected per MeV of deposited energy. Together with border effects in which part of the gamma energy is lost, the energy resolution is expected to be 12 % for a positron with 2 MeV kinetic energy. Simulations have shown that the resolution is anticipated to be the same for each of the target cells. The setup is completed by an active muon veto in form of a water Cherenkov detector on top of the neutrino detector.

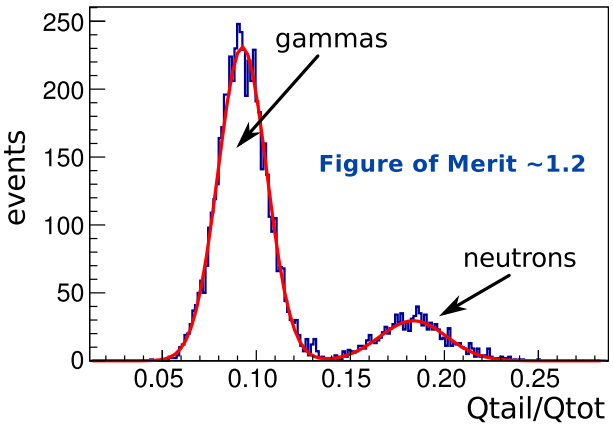

Figure 2. Tail-to-total charge ratio of gamma and neutron events in the Stereo liquid scintillator. The measurement was performed in a 100 cm^3 test cell.

3. Background reduction

The main challenge of a reactor antineutrino measurement close to the core and at shallow depths are the backgrounds. Besides the large flux of cosmic muons and secondary spallation products, the reactor core itself and experimental setups close to Stereo will be the origin of backgrounds in form of gamma radiation and neutrons. Therefore, background suppression is a major task which is accomplished by a number of approaches in the Stereo experiment. In total 72 tons of shielding and neutron absorbers will surround the detector: 65 tons lead, 6 tons polyethylene, and 1 ton B_4C. A water channel above the detector hall provides overburden of about 10 mwe. Additional shielding material is installed at the Stereo site to block radiation created by other nearby experimental setups. The magnetic stray field of neighbouring experiments is eliminated by a magnetic shield surrounding the Stereo detector. Other methods to mitigate backgrounds include analysis techniques and the opportunity to perform a direct cosmic background measurement in reactor-off phases. External backgrounds entering the detector can not only be tagged by the active muon veto, but also using the outer crown volume. Pulse shape discrimination offers the possibility to distinguish gamma and neutron events. Its capability was optimized by the admixture of DIN (di-isopropyl naphtalene) to the liquid scintillator. Fig. 2 shows the tail-to-total charge ratio of gamma and neutron events with a FoM parameter of ~ 1.2.

4. Current status and discovery potential

The experimental site at the ILL has been prepared and first shieldings have been installed. Main components of the detector and of the electronics are finalized, the technical design is finished and prototypes were tested. The Hamamatsu PMTs R5912-100 were validated to meet the required expectations in gain, peak-to-valley ratio, dark rate and afterpulsing. Prototypes exist of the front-end boards, the muon veto and one detector cell. The cell prototype is to scale in height, half the size in width and equipped with two PMTs. Fig. 3 shows the relative attenuation between bottom and top of the detector cell prototype. This test was performed while the cell was either filled with air or liquid scintillator. Between bottom and top the relative attenuation changes by less than 4 %, which demonstrates that the wall reflectivity does not compromise the energy resolution.

The discovery potential of the Stereo experiment is shown in Fig. 4. For this projection the complete detector response was simulated including systematic influences of the neutrino spec-

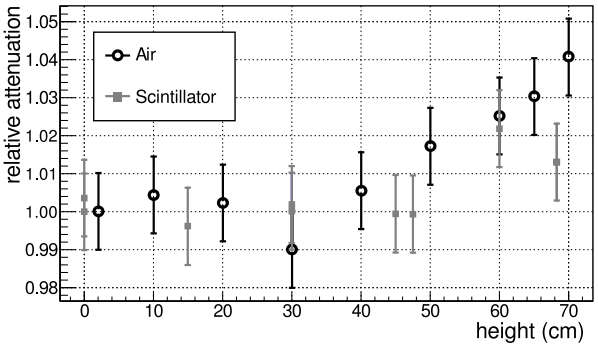

Figure 3. Measured relative attenuation between bottom and top of the detector cell prototype.

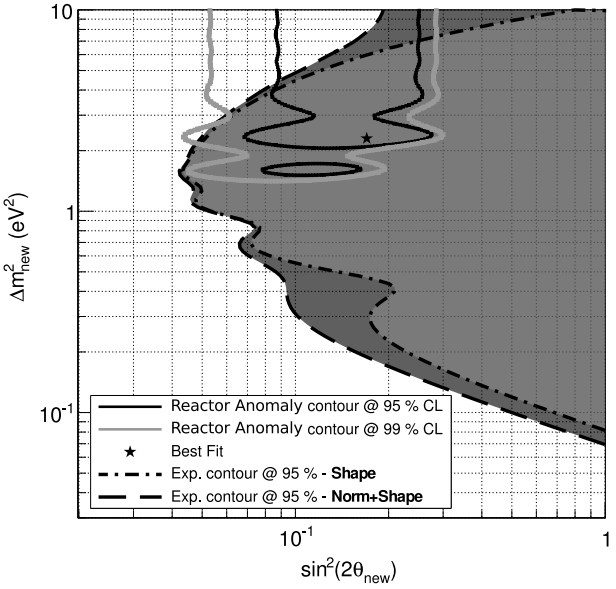

Figure 4. Discovery potential of the Stereo experiment. The accessible parameter space is shown by the grey shaded regions.

tra, the event detection and reconstruction. The selection cuts applied to the prompt signal required $E_{\mathrm{vis}} \geq 2\,\mathrm{MeV}$ and for the delayed signal $E_{\mathrm{vis}} \geq 5\,\mathrm{MeV}$, resulting in a 60 % detection efficiency. Furthermore a signal-to-background ratio of 1.5 was taken into account in the computation. As statistics 300 live-days of collected data were assumed, corresponding to 6 reactor cycles. The accessible parameter space is shown by the grey shaded regions and covers the main region enclosed by the reactor anomaly contours. Including the energy spectrum information in the analysis improves the sensitivity to small mixing angles at large and small Δm^2. The Stereo detector is currently under construction, data taking will start in 2016.

References

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