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Reactor antineutrino fluxes – Status and challenges

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Abstract

In this contribution we describe the current understanding of reactor antineutrino fluxes and point out some recent developments. This is not intended to be a complete review of this vast topic but merely a selection of observations and remarks, which despite their incompleteness, will highlight the status and the challenges of this field.

1. Introduction

The antineutrino flux from a nuclear reactor has become a matter of considerable interest over the past few years. The antineutrinos are created in the beta decay of the neutron rich isotopes produced as fragments in the fission of the reactor fuel. The interest in the resulting electron antineutrino flux originates from two communities. Basic research employs measurement of the flux to investigate neutrino oscillations including the possible existence of sterile neutrinos while the safeguards and threat reduction community would use the neutrino[1] spectrum and its composition over time as indicator of the makeup of the fissile material in the reactor. The basic research focus is on the absolute neutrino flux while safeguards has greater interest in the spectrum shape which may have markers for particular species of the fuel. Significant uncertainty remains regarding both issues. Reactor neutrino experiments rely on inverse beta decay (IBD)

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[1] For the sake of brevity we will refer to electron antineutrinos as neutrinos throughout this paper.

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$$\bar{\nu}_e + p \rightarrow n + e^+ \tag{1}$$

to detect the neutrino. This reaction has a neutrino energy threshold of $E_{\text{th}} \simeq 1.8$ MeV. Any uncertainty in the cross section directly relates to an uncertainty in the detected event rate or measured flux. The existing world average of the absolute value of the measured flux is 6% below the best prediction of that flux [1], which was recently confirmed by Daya Bay [2], which is known as the Reactor Antineutrino Anomaly (RAA).

Three recent very successful experiments (Daya Bay [3], Reno [4], Double Chooz [5]) focused on measuring the neutrino mixing angle θ_{13} and as a by-product provided the most precise and detailed measurements of the neutrino spectrum produced by pressurized water power reactors (PWR). All three measurements used well-calibrated detectors at three different reactor sites and observed an unexpected excess of neutrinos with energies between 4.8 and 7.3 MeV [2]. This result has forcefully brought home the notion that the neutrino fluxes are not as well understood as had been thought. At present, it is not clear what physics gives rise to the bump. It clearly must be attributed to the excess production of some isotope or isotopes with a beta decay end point energy in the interval of the observed bump. There was a belief that the reactor neutrino fluxes could be predicted to within 2%. This belief was founded on employing integral beta spectra measured in the 1980's at the Institute Laue–Langevin (ILL) by K. Schreckenbach and collaborators. They inserted foils of ^{235}U, ^{239}Pu and ^{241}Pu into the ILL reactor to expose them to a thermal neutron flux and directly measured an integral beta spectrum created by the beta decaying isotopes produced by the neutron induced fission of each fissile isotope [6–8]. The beta electron spectroscopy was performed with a magnetic spectrometer which also provide the necessary electron/gamma separation. It is of note that this type of measurement has been pioneered by Reines in 1958 [9] using an anti-coincidence counter based on plastic scintillator; the same technique was employed in a recent measurement of the integral beta spectrum of ^{238}U [10]. Those measurements and the inferred neutrino yield for each fissile isotope can be combined with the evolution of the fissile fuel composition over the run time to make a prediction of the neutrino spectrum. Of course, there are some assumptions and physics required in going from the beta spectrum to the neutrino spectrum but these were presumed to be tractable. Thus, the bump observed in the neutrino flux came as a surprise as no such bump could be generated using the ILL beta spectrum measurements. In principle one could take a different tack from using the ILL measurements and employ information contained in the very large data bases ENDF/B-VII.1 and JEFF-3.1.1 associated with the fission of ^{235}U, ^{239}Pu and ^{241}Pu. These databases pull together a large body of experimental results to establish the fraction of each isotope produced in the fission of a specific fuel element as well as the subsequent beta decay branching ratios for each isotope. Naturally the use of such a procedure produces a large uncertainty in the predicted neutrino spectrum, on the order of 15%, see for instance Ref. [11]. However using ENDF/ B-VII.1 one predicts a bump similar to that observed in the neutrino measurements. As reported in [12] using the JEFF-3.1.1 no such bump is predicted. Reference [12] discusses possible origins for the bump but provides no definite conclusions. Thus the bump in the neutrino energy spectrum that at present cannot be traced to a particular fissile isotope and an apparent 6% deficit in the total measured rate present serious obstacles to the use of neutrino detection for either basic research or threat reduction.

For basic neutrino research, the question is whether the 6% deficit is due to nuclear physics or due neutrino oscillation involving one or several eV-scale sterile neutrinos. The eV-scale sterile neutrino interpretation is also supported by a range of anomalies, where none taken individually is statistically very significant, but which in combination point towards an eV-scale sterile neutrino, for a review see Ref. [13].