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Oscillations at low energies

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Abstract

A concise summary of the "Oscillation at low energies" parallel session at the 2014 Neutrino Oscillation Workshop is provided. Plans to use man-made neutrinos and antineutrinos to determine the neutrino mass hierarchy, search for sterile neutrinos, and to observe coherent neutrino-nucleus scattering were discussed. Potential measurements of solar neutrinos, supernova neutrinos, and geoneutrinos are also summarized.

Keywords: neutrino oscillation, neutrino mass hierarchy, sterile neutrinos, reactor antineutrinos, solar neutrinos, supernova neutrinos, geoneutrinos

1. Introduction

Measurements of the oscillation of reactor, solar, accelerator, and atmospheric neutrinos have given us a fairly consistent picture of the flavor mixing of massive neutrinos [1]. The topics covered during the "Oscillation at low energies" parallel session of the Neutrino Oscillation Workshop focused on the questions addressed by future measurements using low energy neutrinos. Plans are proceeding toward determination of the neutrino mass hierarchy using medium-distance (60 km) oscillation of reactor antineutrinos. Multiple searches for oscillation to sterile states at short-distances (~10 m) from reactor or intense radioactive sources are expected to occur over the next few years. To constrain models of the emission of antineutrinos from nuclear reactors, theorists request additional measurements. Advancements in low-energy-threshold detectors allow for potential measurement of coherent neutrino-nucleus scattering. Solar neutrino measurements are an important ingredient for solar models and for testing the LMA-MSW solution for neutrino oscillations. Supernova neutrinos detection would provide a lot of information about star collapse and neutrino physics, and thus several running and future experiments are focused toward this goal. The effects of decoherence by wave packet separation on complex collective phenomena which could manifest in neutrino oscillations in the extreme supernovae environment have recently been studied. Neutrino geoscience is a new interdisciplinary field aiming to measure the Earth's radiogenic heat, providing an important benchmark for geosciences. These topics are briefly summarized here.

2. Man-made sources of ν and $\bar{\nu}$

2.1. Neutrino mass hierarchy

Due to the non-zero value of θ_{13}, a signature of the neutrino mass hierarchy is present in the oscillation of antineutrinos emitted by nuclear reactors [2, 3]. The neutrino mass-squared differences $\left|\Delta m^2_{ji}\right| = m^2_j - m^2_i$ cause energy-dependent $\bar{\nu}_e$ disappearance, introducing a distortion of the reactor $\bar{\nu}_e$ energy spectrum. The oscillation frequencies caused by $\left|\Delta m^2_{31}\right|$ and $\left|\Delta m^2_{32}\right|$ differ by only 3% according to measurements of $\left|\Delta m^2_{21}\right|$. Measurements of the mixing angles predict that the $\bar{\nu}_e$ oscillation amplitude from $\left|\Delta m^2_{31}\right|$ is twice as large as that from $\left|\Delta m^2_{32}\right|$. The mass hierarchy can be discerned by whether the smaller-amplitude $\left|\Delta m^2_{32}\right|$ oscillation is at a slightly lower (normal) or higher (inverted) frequency. Discrimination of these two frequencies from the distortion of the reactor $\bar{\nu}_e$ energy spectrum is most

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pronounced at the first $\left|\Delta m^2_{21}\right|$ oscillation maximum, or roughly ~60 km from a reactor.

Two experiments have been proposed to determine the mass hierarchy using reactor $\overline{\nu}_e$: the Jiangmen Underground Neutrino Observatory (JUNO) [4] and the RENO-50 experiment [5]. The JUNO experiment will be located in an new underground laboratory (700 m rock overburden) in Kaiping city, Jiangmen region, Guangdong province in southern China. Reactor antineutrinos will be produced by the Yangjiang and Taishan commercial reactor facilities, each located 53 km from the planned site. Each facility will have six reactors, with a total power of 17.4 $\mathrm{GW_{th}}$ and 18.4 $\mathrm{GW_{th}}$ respectively. Both facilities are currently under construction, with 26.6 $\mathrm{GW_{th}}$ of power in operation by 2020.

As designed, the JUNO detector consists of a 20 kton target of liquid scintillator contained in a 35.4 m-diameter transparent acrylic sphere. Light produced by $\overline{\nu}_e$ interactions in the target is detected by 15000 20-inch photomultiplier tubes (PMTs) mounted on a stainless steel frame surrounding the target. The entire system is contained within an active water Cherenkov veto detector, instrumented with 1500 additional PMTs. A secondary planar veto detector rests above the Cherenkov detector. Approximately ~40 reactor $\overline{\nu}_e$ inverse beta decay interactions per day are predicted within the target volume. Preliminary estimates for background from accidentals, fast neutrons, and long-lived spallation isotopes are ~10%, 0.4%, and 0.8% respectively.

According to Ref. [6], after six years of operation the JUNO experiment can discriminate between the two hierarchies with a $\Delta\chi^2 > 9$. By 2020, existing experiments may measure $\left|\Delta m^2_{32}\right|$ with 1.5% precision. Including this external constraint, the JUNO sensitivity is predicted to improve to $\Delta\chi^2 > 16$. The sensitivity of the experiment is strongly dependent on the energy resolution of the detector. Statistical fluctuation in the number of detected photons is predicted to limit the resolution. To achieve the desired energy resolution of $3\%/\sqrt{E[\mathrm{MeV}]}$, the JUNO detector must collect an average of five times more photons than Daya Bay detectors. Current research and development is focused on increasing the collected light by scintillator purification to reduce light attenuation, exploring new designs for high efficiency PMTs, and maximizing the PMT surface coverage. The mechanical integrity, stresses, and aging of the acrylic target container are also under study. To reduce the cabling required for the large number of PMTs, the collaboration is testing prototype electronics for underwater installation close to the PMTs. Aside from the mass hierarchy, the JUNO experiment intends to measure θ_{12}, $\left|\Delta m^2_{21}\right|$, and $\left|\Delta m^2_{31}\right|$ to better than 1% precision. Measurements of solar neutrinos, atmospheric neutrinos, geoneutrinos, sterile neutrinos, proton decay, and other exotic models are being explored.

The JUNO experiment has obtained the land for the detector site and completed a geologic survey. The civil design is almost complete, and construction is expected to begin soon and complete in 2017. Detector construction is planned for 2017 through 2019. Filling of the detector with liquids and collection of the first data is planned for 2020.

2.2. *Sterile neutrinos*

Measurements of the the emission of antineutrinos from nuclear reactors show a deficit relative to recent estimates [7]. A similar deficit has been observed in geochemical measurements of neutrinos from intense radioactive sources [8]. Combined, these discrepancies have been interpreted as possible evidence of oscillation to hypothetical sterile neutrino states [9].

On average, six $\overline{\nu}_e$ are emitted by the beta decays of the fragment isotopes from a single fission. Direct calculation of reactor $\overline{\nu}_e$ emission is complicated by the lack of detailed knowledge of the energy levels and decay spectra for the ~10000 unique beta decays which contribute. Instead, existing models rely on prediction of the cumulative $\overline{\nu}_e$ flux using measurements of the corresponding cumulative β^- emitted by fissioning isotopes [10, 11]. These predictions account for weak magnetism, radiative, finite nuclear size, and screening corrections which impact the correspondence between the β^- and $\overline{\nu}_e$ energy spectra. Recent reevaluation increased the predicted $\overline{\nu}_e$ flux by 6% relative to previous estimates. Half of the increase is a result of improved modeling of the correlation between the cumulative energy spectra of β^- and $\overline{\nu}_e$ from fission fragments. The remaining increase is caused by inclusion of long-lived fission daughter isotopes, and updated measurements of the neutron lifetime which increase the predicted cross section for $\overline{\nu}_e$ interaction with the detector. Measurements of the reactor $\overline{\nu}_e$ flux are on average 6% lower than these recent predictions.

Preliminary measurements of the energy spectra of reactor $\overline{\nu}_e$ reported this past summer disagree with the prevailing models [13, 12, 14]. In particular, the data show a ~10% excess in the region of 5 to 7 MeV relative to prediction. An alternate model relying on direct calculation using the ENSDF nuclear database predicts a spectrum consistent with these measurements, although uncertainties in this calculation are significant [15]. Direct calculations of the corresponding β^- spectra also disagree with the measurements from Refs. [16, 17, 18].