PROCEEDINGS OF SCIENCE

Research and Development Studies for Reactor Neutrino Experiments in Turkey (RNET)

Ayse Bat,[a,*] **Emrah Tiras,**[a,b] **Vincent Fischer**[c] **and Mirac Kamislioglu**[d]

[a]*Erciyes University,*
38030, Kayseri, Türkiye
[b]*The University of Iowa,*
52242, Iowa City, Iowa, USA
[c]*Fermi National Accelerator Laboratory,*
60510, Batavia, IL, USA
[d]*Bandırma Onyedi Eylül University,*
10200, Bandırma,Türkiye

E-mail: aysebat@erciyes.edu.tr, abat@fnal.gov

The program of the Reactor Neutrino Experiments of Turkey includes a small portable Water-based liquid scintillator detector to detect neutrinos from the Akkuyu nuclear power plant, planned to begin operating in 2023. The small near-field detector will weigh about 2-3 tons and will be placed less than 100 meters from the reactor cores. The Reactor Neutrino Experiments of Turkey program also includes a medium-size 30-ton Water-based liquid scintillator detector, which will be placed 1-2 km away from the reactor cores and will be used as a far detector. Both detectors and their responses to neutrino interactions were simulated using a GEANT4-based RAT-PAC simulation package. Here, we will share the technical and physical details of both detectors, and discuss the ongoing R&D effort for neutrino studies in Turkey.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

*Speaker

PoS(ICHEP2022)623

1. Introduction

Neutrino research has gained enormous importance over the last decades. Because of the mystery of their masses, their potential to solve neutrino/antineutrino asymmetry, and also to prove CP violation, researchers from all over the world are trying to unravel the nature of neutrinos with new detector technologies and analysis methods. A water-based Liquid Scintillator (WbLS) is one of the new detection media aimed to enrich our physics potential [1]. A WbLS is a stable mixture of water and scintillator, both acting as, detection media, which was first developed and manufactured at Brookhaven National Laboratory. Water and scintillator are not liquids that mix naturally and homogeneously, hence the need for an additional component, a surfactant like PRS (Linear Alkyl Sulfonate), to reduce the surface tension within the liquid. When surfactants come into contact with water and scintillator, they create "micelles" which can be miscible with the aqueous solution and hold the scintillator molecules. This procedure allows WbLS to be a homogeneous mixture [2]. One of the key advantages of WbLS is that it can combine the benefits of both water Cherenkov and liquid scintillator technologies in one detector. For this reason, WbLS can simultaneously provide unique features such as the ability of a Cherenkov detector to detect a particle's direction, as well as the high light yield efficiency and low threshold of the scintillator [3].

2. Akkuyu Nuclear Power Plant

Nuclear reactors have a very important role to play in neutrino physics due to being an extremely intense source of low-energy electron anti-neutrinos. The Akkuyu Nuclear Power Plant (ANPP), soon to be operated in Turkey, will create a good opportunity to work on neutrinos at low energies. The ANPP will be the first power plant in Turkey and is under construction on the southern coast of Turkey in the Mersin province. The nuclear power plant is going to be operational in 2023. The ANPP will consist of four power units equipped with a Water-Water Energy Reactor (VVER-1200) with a total capacity of 4800 MW_e [4, 5].

Electron anti-neutrinos ($\bar{\nu_e}$) produced by beta decays of fission reactions in nuclear reactors are detected via Inverse Beta Decay (IBD) ($\bar{\nu} + p \rightarrow e^+ + n$). This reaction leads to the creation of two different signals, one from the positron and the other from the neutron, both separated in time and having different signatures. The first signal comes from the energy deposition of the positron and then its annihilation on an electron in the medium, resulting in two 511 keV gamma-ray emissions. This is called a prompt signal, E_{prompt}. The second signal, produced by the neutron capture on an atom in the medium, occurs a few microseconds ($\sim$ 10-100 μs depending on the detection environment) after the first signal. A neutron capture on hydrogen releases 2.2 MeV of energy and a neutron capture on Gd releases a gamma cascade with a total energy of about 8 MeV. These are called delayed signals, $E_{delayed}$. For this reason, as well as its high neutron capture cross-section, when designing detectors, Gd is often considered an isotope of choice to dope detector media.

3. Reactor Neutrino Experiments in Turkey

The goal of the Reactor Neutrino Experiments in Turkey (RNET) program is to establish a long-term research program on low-energy reactor neutrinos, which includes a small-size short-distance detector and a medium-sized long-distance detector. Both detectors will have a similar design, and the main goal of these detectors is to test new detector technologies such as WbLS, and Large Area Picosecond Photodetectors (LAPPDs) [6], etc.

4. Simulation Studies and Detectors Design

The RAT-PAC [7] simulation program has been used for optimizing the detector design and simulating the detector response to Inverse Beta Decay events. The RAT-PAC framework utilizes the GEometry ANd Tracking (Geant4) and GLG4Sim libraries to handle the physics process, particle tracking, construction of detector geometries, and other aspects of the simulation. The medium-sized far detector of RNET consists of a 30-ton cylindrical volume with a height of 4.3 m and a diameter of 3 m. In the simulation, the detector volume was filled with a WbLS mixture loaded with 10% liquid scintillator content and 0.1% Gd gadolinium doping. It is equipped with 227 10-inch High Quantum Efficiency (HQE) PhotoMultiplier Tubes (PMTs) that provide total photo coverage of approximately 30%. It is planned to be installed approximately 100 meters underground and about 1 km away from the reactor cores[8]. The tank of the small-size near detector is a cylindrical stainless steel tank 1.5 m high and 1.5 m wide, filled with WbLS. After trying different percentages of scintillator content in WbLS, simulation studies were carried out with a 3% liquid scintillator and 0.1% Gd-loaded WbLS loading. 24 8-inch R5912 HQE PMTs were used inside the detector. 8 of them were placed on top and bottom of the detector, and 16 on its side walls. With this design, the detector provides 28% photo coverage [9]. Figure 1 shows both these designs that were made by using RAT-PAC simulation program.

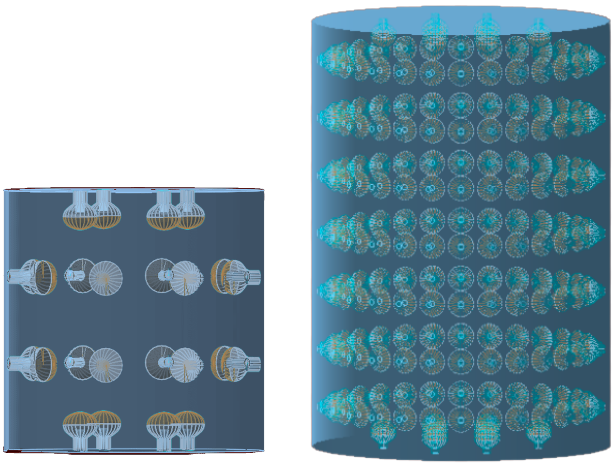

Figure 1: The left figure shows the small-size near detector [9] and the right figure shows the medium-size far detector design [8]. Note that the figures are not scaled.

To understand the physics response of the Gd-doped WbLS detectors, we simulated several physics events such as monoenergetic electrons as well as IBD events. IBD events were simulated at the center of the detector to understand the detector response and efficiency in detecting reactor neutrinos. Electrons were simulated uniformly in the detector and at fixed energies to determine the conversion factor between the number of photon hits and the visible energy in MeV. For this purpose, the simulated electron energy spectra were fitted with the best Gauss+Landau functions.

A mean of 15 photo-electrons (p.e.) per 1 MeV electron was obtained using this fit. Figure 2 shows the photo-electron distribution of 1 MeV electrons simulated uniformly in the inner fiducial volume of the detector and the fit Gauss+Landau function to describe the distribution.

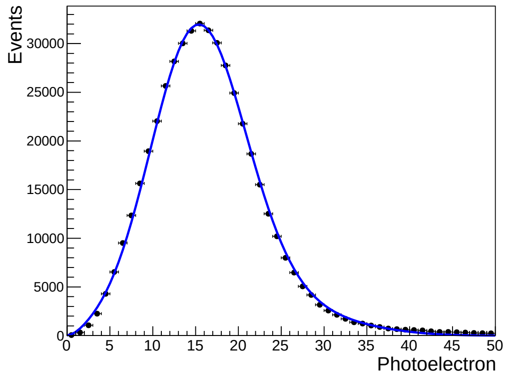

Figure 2: Photo-electron distribution of 1 MeV electrons simulated uniformly in the inner fiducial volume of the detector [9].

To obtain prompt and delayed photoelectron distributions, time cuts were applied during the analysis. The 0-200 ns time interval was selected as the prompt window, and the 1-200 μs time interval was selected as the delayed window. The scale factor of 15 p.e. obtained earlier was used to obtain the energy distributions of these signals. Figure 3 shows the reconstructed prompt and delayed event energy distributions from simulated IBD events. The prompt energy distribution corresponds to the visible energy deposited by positrons in the detector. As one can expect from a WbLS medium doped with Gd, the delayed energy distribution shows two structures: the narrow 2.2 MeV peak from neutron captures on H, and the broader peak from neutron captures on Gd centered around 8 MeV. The time difference between the prompt and delayed events was observed as having a mean decay time of $\sim$ 24 μs [9], due to the high concentration of Gd.

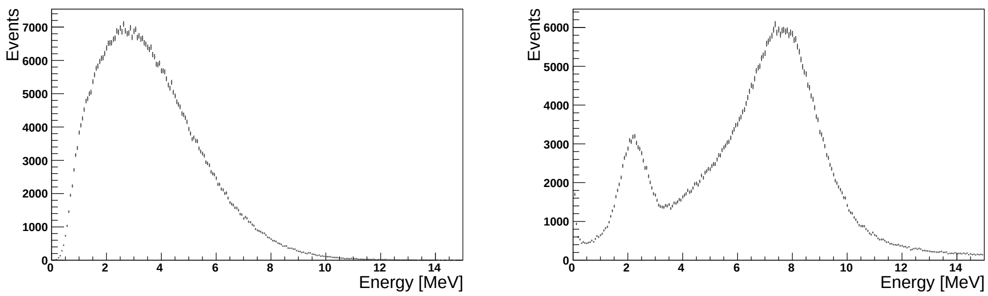

Figure 3: Reconstructed prompt events energy distribution (left), and delayed events energy distribution (right) from the simulated IBD events [9].

5. Conclusion

In this paper, we present the Reactor Neutrino Experiments of Turkey program in terms of detector design, preliminary simulation studies, aim, and scope. Both detectors are considered as testbeds for new neutrino detector technologies such as water-based liquid scintillators, large area picosecond photodetectors, and other future technologies based on light detection in water-based or oil-based media. The simulation studies show that a 3-ton water-based liquid scintillator detector is capable of efficiently detecting both prompt and delayed signals from inverse beta decay events. The small-size near-field detector of the Reactor Neutrino Experiments of Turkey program was recently funded by the national Tubitak 1001 project and its construction will be started in 2023.

6. Acknowledgements

This work was supported by Scientific Research Projects (BAP) of Erciyes University, Turkey under the grant contract of FDS-2021-10856. It could not have been accomplished without the support and resources of Erciyes University. The authors owe special thanks to the WATCHMAN Collaboration for the WATCHMAN version of the open-source RAT-PAC simulation program. The authors would also like to thank The Orebi Gann group at UC Berkeley for developing and providing the WbLS cocktails in the WATCHMAN GitHub.

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