Upgrade of OSIRIS for Future Liquid Scintillator Studies

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Understanding the internal radioactive background contributions in its 20 kiloton liquid scintillator (LS) target is essential for the success of the JUNO reactor neutrino experiment. OSIRIS is a 20-tonne radiopurity detector at the end of the JUNO LS purification chain. It will screen 1/10 of the LS during JUNO filling and verify that its internal radiopurity requirements of are met. Once filling is complete, OSIRIS, in combination with the existing LS purification infrastructure, will serve as an excellent testbed for various types of LS studies and, in particular, for the development of JUNO's future physics programme. Scenarios considered so far range from long-term LS stability or double beta decay isotope loading tests to stand-alone precision measurements of the solar pp neutrino flux. To maximise the results of such measurements, cost-effective improvements to the OSIRIS detector are needed. For example, to improve the uniformity of light collection, the cylindrical photodetector configuration will be changed to a spherical one. Light collection will be improved by adding light concentrator cones and additional PMTs. The addition of external shielding will help to suppress the external gamma-ray background in the central volume of the detector. This paper discusses in more detail the planned improvements and physics cases for the OSIRIS upgrade.

XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP2023)
28.08–01.09.2023
University of Vienna

*Speaker

PoS(TAUP2023)319

1. Introduction

The OSIRIS detector [1] is a subsystem of the liquid scintillator filling chain of the JUNO neutrino experiment [2]. Its purpose is to validate the radiopurity of the liquid scintillator (LS) to be filled into the JUNO central detector. This will ensure that all components of the scintillator purification system are working to their specifications, that the targeted radiopurity level of 10^{-15} to 10^{-17} (reactor to solar) of ^{238}U and ^{232}Th is achieved, and that JUNO's ambitious precision measurement of the neutrino mass ordering (NMO) can be pursued. The detection of such ultra-low background levels requires a large ($\sim$ 20 m^3) detection volume. The design of the OSIRIS detector with its main components, i.e., the acrylic vessel containing the LS sample, the photomultiplier systems mounted on the steel frame inside the water buffer volume (outer tank), is shown in Figure 1. The OSIRIS detector is currently in the commissioning phase at the JUNO site and is scheduled to complete its LS screening task during 2024. In view of the advancing schedule, discussions have started on the further use of this extensive existing infrastructure.

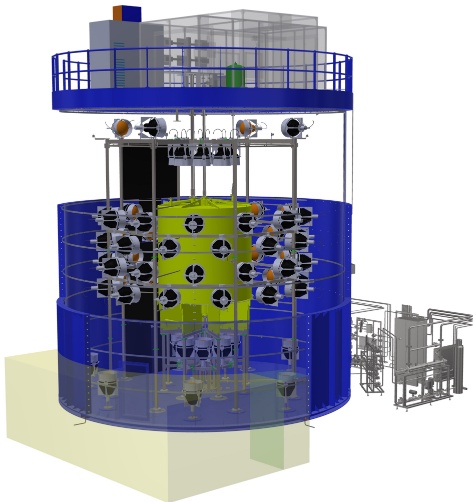

Figure 1: Schematic layout of the current design of the OSIRIS radiopurity detector showing the main components of the experiment. The acrylic vessel, which contains the 20-tonne LS sample (highlighted in yellow at the center), is surrounded by the steel structure supporting an array of 76 20-inch MCP photomultipliers. This setup is enclosed by a 9 meter high carbon steel tank (highlighted in blue) filled with water.

2. Considered Upgrades

To maximise the potential of the existing infrastructure, several low-cost improvements are considered to suppress internal and external backgrounds and improve light collection efficiency. Light collection and uniformity can be improved by rearranging the PMTs in a spherical configuration and adding light collection cones. There is also the possibility of incorporating additional photomultipliers up to a total of ~150. Light collection efficiency studies have been started for the spherical PMT configuration and to optimise the shapes of the light collection cones. An example of such a study and the light collection efficiency achieved is shown in Figure 2. The addition of a layer of material equivalent to about 15 cm of stainless steel outside the OSIRIS water tank is considered to further suppress the external gamma background from the surrounding rock. Replacing the rather thick (3 cm) acrylic vessel containing the LS sample with the Borexino-like nylon balloon would provide additional internal gamma background suppression. The magnitude of the external and internal gamma backgrounds and the required level of suppression will become clear when the

OSIRIS begins its measurements. Other improvements would include the use of a low-^{14}C LS and the use of a slow LS.

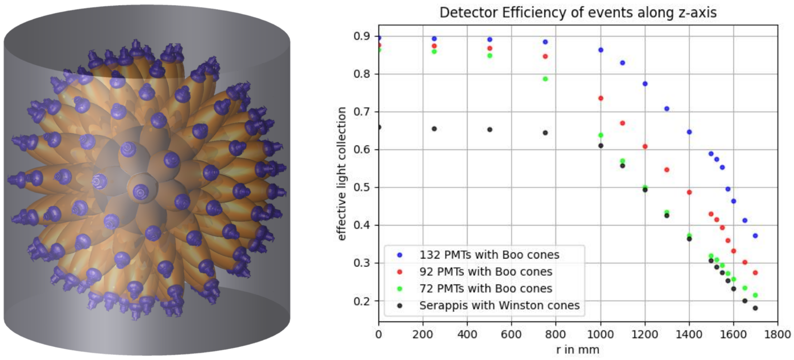

Figure 2: Left: Illustration of the spherical PMT configuration of the OSIRIS upgrade with 132 photomultipliers equipped with Boolean cut light concentrators (Boo cones). Right: Comparison of the effect of the different PMT configurations equipped with of Boo cones on the light collection efficiency using ray tracing software (blue, red and green). The original Serappis design [3] using traditional Winston cones is shown in black.

3. Considered Physics Use Cases

In addition to the R&D of liquid scintillator materials at the 20-tonne scale, the upgraded OSIRIS could offer two interesting ways to complete the JUNO physics programme: a stand-alone solar $pp - \nu$ flux measurement and preliminary studies related to neutrinoless double beta decay (JUNO Phase II).

The measurement of solar $pp - \nu$ flux has been discussed conceptually in [3]. We have identified a number of advantages to having a smaller detector to improve the current measurement of Borexino ($\sim$ 10%) [4]. The smaller mass of the detector volume would in principle allow a more careful selection of the low-^{14}C raw material for the LS. The smaller LS volume will also lead to less pile-up of spectral components. Finally, higher photoelectron yield and light collection efficiency will result in better energy resolution and more accurate spectral fitting. Our Monte Carlo studies show that in the standard scenario described in [3], the uncertainty in the solar $pp - \nu$ flux would be reduced from the current level to 3.4%. In the most optimistic case, 1-2% is achievable, allowing complementary oscillation parameter measurements and model-independent testing of the standard solar model. To further improve sensitivity, the application of Correlated and Integrated Directionality (CID)[5] is being investigated.

The OSIRIS upgrade could also serve as a testbed for the JUNO's $0\nu\beta\beta$ programme, which uses the electron-emitting double beta decay of tellurium isotopes. For example, it is essential to study the isotope loading of the LS, its stability and its effect on the optical properties of the LS in the long term on a larger scale (20 tonnes). The recently introduced slower LS will also allow the separation of the Cherenkov and scintillation photons and provide a handle on the event direction, better event classification and improved background discrimination. An upgraded OSIRIS could serve as a testbed for the reconstruction algorithms and data analysis. Figure 3 illustrates the priciple of scintillation and Cherenkov separation in the case of ^{130}Te compared to standard spectral shape analysis. The spectral components form bands depending on the final state particles and their energies. Finally, loading the slow scintillator with e.g. ^{78}Kr or ^{124}Xe isotopes would open the possibility to study positron emitting double beta decays by tagging the annihilation gammas. This would be of general interest to nuclear physics and nuclear structure modelling.

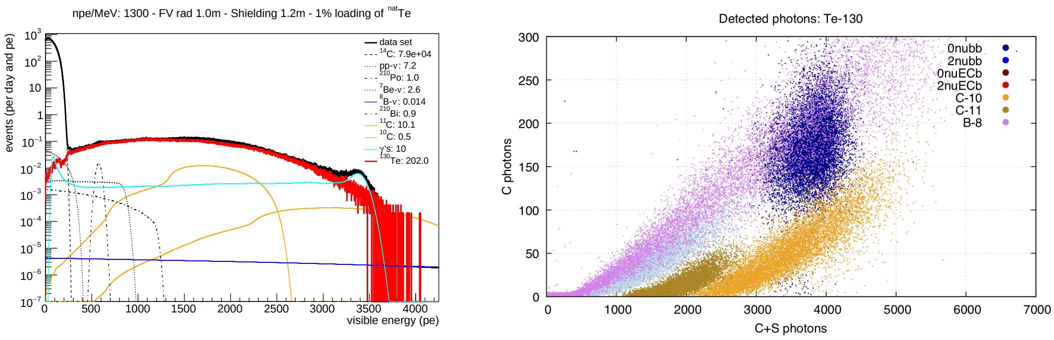

Figure 3: Illustration of the additional power of scintillation-Cherenkov separation compared to normal spectral analysis in the case of the double beta decay of ^{130}Te.

4. Summary and Outlook

The OSIRIS radiopurity detector will test the quality of the JUNO LS. Once JUNO's central detector is filled, this extensive infrastructure will be available for other research. The process of outlining the future use of OSIRIS has begun and interesting targets such as a stand-alone solar $pp - \nu$ measurement or a 20 tonne R&D testbed for different types of LS development studies have been found attractive. To ensure the success of future use, some moderate improvements are required, such as repositioning of the PMTs and replacement of the LS vessel. Work is underway to assess the physics goals and more realistic scenarios once the first real measurements are made.

References

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