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CLOUD: the First Reactor Antineutrino Experiment using the Novel LiquidO Detection Technology

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The CLOUD collaboration is pioneering the first fundamental research reactor antineutrino experiment using the novel LiquidO technology for event-wise antimatter tagging. CLOUD's program is the byproduct of the AntiMatter-OTech EIC/UKRI-funded project focusing on industrial reactor innovation. The experimental setup comprises an up to 10 tonne detector, filled with an opaque scintillator and crossed by a dense grid of wavelength-shifting fibres. The detector is expected to be located at EDF-Chooz's new "ultra-near" site, 35 m from the core of one of the most powerful European nuclear plants, with minimal overburden. Detecting of order 10,000 antineutrinos daily and with a high (100) signal-to-background discrimination, CLOUD aims for the highest precision of the absolute flux, along with explorations beyond the Standard Model. Subsequent phases will exploit metal-doped opaque scintillators for further detection demonstration, including the first attempt at surface detection of solar neutrinos.

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1. Introduction

The CLOUD (Chooz LiquidO Ultra near Detector) experiment represents a new frontier in neutrino physics, focusing on precise measurements of neutrino interactions using the novel LiquidO technology [1]. Following the CHOOZ and Double Chooz experiments, CLOUD embodies the third generation of neutrino fundamental studies at the Chooz nuclear power plant, which remains the leading site in Europe for reactor neutrino research. The experiment is supported by an international collaboration, including the involvement of the nuclear reactor operator EDF. CLOUD is the fundamental physics front of the innovation-driven AntiMatter-OTech project [2], which has been conceived for industrial applications, specifically reactor monitoring, and has been funded by the European Innovation Council (EIC) and UK Research and Innovation (UKRI). Therefore, the CLOUD experiment can be seen as the byproduct of the AntiMatter-OTech project, since we intend to make use of part of the data collected by the AntiMatter-OTech detector to carry out our fundamental neutrino physics analyses.

The detector is expected to be positioned at the Ultra Near site, adjacent to the Chooz reactor core, with a baseline of around 35 meters, with ~3 m.w.e. overburden. This setup faces unique challenges, as the detector will operate at the surface and be exposed to significant background, such as cosmic muons and atmospheric neutrons. Despite these drawbacks, its innovative design, particularly its integration of the LiquidO technology, offers promising solutions to achieve unprecedented precision measurements. CLOUD aims to explore neutrino properties across different sources and this proceeding provides an overview of the project, outlining its three-phase physics program: Phase-I is devoted to reactor antineutrino measurements, with Phase-II and Phase-III focused on the feasibility of detecting solar neutrinos and geoneutrinos.

2. The CLOUD experiment and LiquidO detection technique

LiquidO is a novel particle detection technology, offering a unique alternative to traditional neutrino detectors using transparent media. Whereas conventional reactor neutrino experiments rely on clear liquid scintillator that allow light to travel to the photo-sensors located on the detector walls, LiquidO uses an opaque medium with a short scattering length that confines the light near its creation point, forming a localized "light ball". The light is then collected by a dense array of wavelength-shifting (WLS) fibres and read out by Silicon Photomultipliers (SiPM) and very fast electronics. In this way, LiquidO will enable event-by-event topological discrimination power, with highly efficient particle identification (PID), including positron, electron and gamma events, as described in the first publication of the international LiquidO consortium Ref. [3] and displayed in Figure 1.

The stochastic light confinement with a 10-litre LiquidO prototype has been demonstrated in [4], which was a critical condition for the success of CLOUD. This prototype has been able to contain a single-point-like light-ball, formed upon the injection of single electrons with controlled energy up to 2 MeV.

The AntiMatter-OTech detector, currently being designed, is expected to be an of order 10 tonne detector filled with a LAB (Linear Alkylbenzene) + PPO fluor based opaque scintillator. Light is captured by tens of thousands of WLS fibers, coupled to SiPMs on both ends, allowing

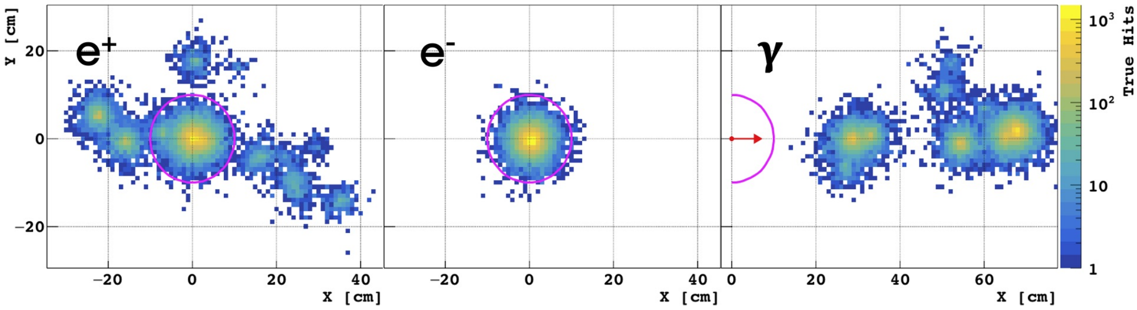

Figure 1: LiquidO PID. Event pattern of a positron, an electron and a gamma with 2 MeV of kinetic energy is simulated on a default LiquidO detector configuration, with a 5 mm scattering length opaque scintillator and fibres arranged in a 1 cm pitch lattice running along one axis. The colour of each point represents the number of photons hitting a fibre at that x-y location. The e^+ is identified thanks to its annihilation signature, while the spatially dispersed Compton-scattering pattern of the γ sets it apart from the e^-. Being able to distinguish e^+ from e^- implies neutrino and antineutrino discrimination as well. More details can be found in [3].

millimeter-scale vertex resolution. This design enhances event reconstruction capabilities and improves background discrimination, making it suitable for the challenging environment of the project.

Another key feature of LiquidO is its high-level doping acceptance, as transparency is no longer required. This characteristic opens a wide range of possibilities for neutrino physics at the MeV scale and beyond and will be essential for the success of Phases II and III of the CLOUD experiment.

3. CLOUD Phase-I: Reactor Neutrino Precision Measurements

Nuclear reactors are the most intense source of low-energy electron antineutrinos ($\bar{\nu}_e$), generating them through a cascade of β decays of the fission products. A typical commercial reactor core emits a flux of $\sim 10^{20}$ $\bar{\nu}_e/\mathrm{s}$, following the beta decay process of the neutron-rich fission fragments of U and Pu isotopes. Reactor neutrino experiments have reported shape spectral discrepancies between the predicted and measured reactor antineutrino spectra, with a $\sim$15% excess of events in the spectrum around 5-7 MeV. Achieving consistency between the reactor antineutrino flux and energy spectra with experimental data requires more effort from both theoretical and experimental perspectives.

Phase-I of CLOUD is focused on reactor antineutrino detection, aiming for the most precise measurement of the reactor antineutrino flux to date. By placing the envisaged 10 tonne detector just 35 meters from the reactor operating at full thermal power (4.25 GW/h), we expect to collect around 10,000 $\bar{\nu}_e$ per day, through their interaction with a proton of the opaque scintillator via the Inverse Beta Decay (IBD) process: $\bar{\nu}_e + p \rightarrow e^+ + n$. This interaction results in two spatially and temporally coincident signals, with a prompt positron emission and a delayed neutron capture emitting a 2.2 MeV gamma.

Using the LiquidO technology, CLOUD will be able to distinguish the antineutrino signals, characterised by positron annihilation, from background events mainly defined as electron and gamma interactions, which is essential for achieving the high signal-to-background (S/B) ratio necessary for CLOUD's goals. Compared to the Double Chooz experiment [5], which was located 400 meters from the same nuclear power plant with an overburden of 30 m.w.e. and achieved a S/B ratio of 30, CLOUD aims to triple this performance, with the potential to achieve a signal-to-background ratio greater than 100 when the reactor is on.

As said above, we will strive to improve the current best measurement of the absolute reactor antineutrino flux, which has been obtained by Double Chooz (~1% error). With two months of data taking, the detector is expected to reach a statistical power precision of <0.1%, which will help to better constrain most of the systematics uncertainties related to the measurement of the absolute flux (i.e., selection systematics or background subtraction).

Furthermore, we aim to carry out an isotopic decomposition of the $\bar{\nu}_e$ spectra obtained during the reactor on-off transition, with a projected S/B ratio greater than 1. This novel information could serve as a valuable nuclear physics benchmark that may guide the identification of incorrect or incomplete nuclear datasets or impose new constraints on the properties of these isotopes, with the final purpose of validating the reactor models.

In addition to inverse beta decay, CLOUD will also study the antineutrino interactions via electron elastic scattering: $\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$. While this channel is more susceptible to background contamination, as the final product is a single electron, we will need to apply conservative energy cuts to preserve the purity of the measurements. Furthermore, the high-rate reactor modulation can be exploited as an extra tool to improve the S/B, taking advantage of the non-dependency of the backgrounds with the reactor thermal power. Over the course of a year, approximately 20,000 antineutrino events detected via this channel could be available for CLOUD, allowing for a precise measurement (≤10%) of the weak mixing angle at low energies (~4 MeV) using antineutrinos and could help to assess the discrepancy found by the NuTeV collaboration [6], as the measurement of $sin^2\theta_W$ was 3σ higher than the Standard Model prediction.

Lastly, the pioneering development of the AntiMatter-OTech detector and the final demonstration of the S/B high-power discrimination, will provide the experimental feasibility to one of the most important conditions behind the explorations of the SuperChooz experiment [7], an international project conceived as a ground-breaking flagship neutrino experiment in Europe designed to yield some of the world's most precise measurements regarding solar and reactor neutrino oscillations.

4. CLOUD Phase-II: Solar Neutrino Detection

Phase-II of CLOUD is devoted to solar neutrino measurements, particularly those originating from the pp and ^{7}Be processes. This phase, under feasibility study, is beyond the scope of the AntiMatter-OTech project, but it might be seen as a possible future extension requiring minimal modification to the baseline detector. To enable solar neutrino detection, the scintillator will be doped with Indium, taking advantage of the interaction proposed by Raghavan: $\nu_e + {}^{115}\mathrm{In} \to {}^{115}\mathrm{Sn}^* + e^-$ [8]. In this process, electron neutrinos interact with indium nuclei, producing a prompt electron signal followed by the de-excitation of ^{115}Sn (~4.8 s) leading to a double delayed emission with either an electron or a gamma (116 keV) along with a more energetic gamma (497 keV). This triple coincident signal provides a distinct signature that can be effectively separated from background noise. The unique low threshold of this reaction (114 keV) allows access to nearly 95% of the pp ν_e spectrum.

While never observed, a few decades of R&D were dedicated to this detection methodology, whose latest results were reported by the LENS collaboration [9]. With a 10 tonne detector containing 10% indium doping, CLOUD has potential to be the first experiment capable of exploiting the ^{115}In interaction, detecting approximately 25 pp solar neutrino events and 9 ^{7}Be events with one year of collected data. The only expected contamination in the low-energy region, according to LENS' background model, is the coincidence of two intrinsic ^{115}In β-decays, which can be highly suppressed by the triple coincidence enhanced with the PID power of LiquidO technology.

Hence, CLOUD will seek to demonstrate the feasibility of this channel and this method could pave the way for larger detectors, such as SuperChooz, enabling high-precision solar neutrino spectroscopy.

5. CLOUD Phase-III: Geoneutrino detection feasibility

In Phase-III, CLOUD aims to explore a novel method for geoneutrino detection by doping the detector with copper, following the original study made by the LiquidO collaboration, reported in Ref. [10] as a new proposal for possible measurement of ^{40}K geoneutrinos. This charge current process $\bar{\nu}_e + {}^{63}\text{Cu} \rightarrow {}^{63}\text{Ni}^* + e^+$ allows the detection of the antineutrino signal and, thanks to the event topology of the delayed 87-keV gamma ray from the de-excitation of Nickel, we can discriminate it from the neutron capture of the IBD interaction on protons. The copper interaction lowers the IBD threshold to 1.2 MeV, opening up the possibility of measuring previously inaccessible regions of the antineutrino spectrum. We plan to evaluate this channel using reactor neutrinos as a test-beam, and if successful, this could lead to the future detection of ^{40}K geoneutrinos on a much larger detector (order of ktons), which has never been observed before.

The ability to detect potassium geoneutrinos would provide an unique insight into the Earth's internal heat production and geophysical processes, such as the behaviour of volatile elements during Earth's early-stage formation, making Phase-III a potentially groundbreaking contribution to both neutrino physics and Earth science.

6. Conclusion

The CLOUD experiment has been conceived to make significant contributions across multiple areas of neutrino physics, from reactor antineutrino studies to investigating the feasibility of detecting solar neutrinos and geoneutrinos. The innovative LiquidO technology is the cornerstone of this effort, providing the necessary tools to overcome the challenges posed by high-rate background contamination, as the detector will operate on surface, and enabling the high-doping needed to explore new interaction channels. Through its three-phase program, CLOUD has the potential to address the shape discrepancy in the reactor antineutrino field, demonstrate a promising methodology for solar neutrino detection, and explore uncharted territories in geoneutrino research.

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