Snowmass2021 - Letter of Interest

LiquidO: a Novel Approach to Detecting Neutrinos

NF Topical Groups: (check all that apply □/■)

□ (NF1) Neutrino oscillations
□ (NF2) Sterile neutrinos
□ (NF3) Beyond the Standard Model
■ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
□ (NF6) Neutrino cross sections
■ (NF7) Applications
□ (NF8) Theory of neutrino physics
□ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
□ (Other) *[Please specify frontier/topical group(s)]*

Contact Information:
Anatael Cabrera (LAL, Irène Joliot-Curie Laboratoire) [anatael@in2p3.fr]
Juan Pedro Ochoa-Ricoux (University of California, Irvine) [jpochoa@uci.edu]
Collaboration: LiquidO

Authors: a full author list is included after the references.

Abstract: This Letter summarizes a new paradigm in neutrino detection called LiquidO. In this approach, a volume is filled with an opaque scintillator that confines light near its creation point, preserving the topological information of particle interactions. A dense array of optical fibres traverses the volume and collects the light. The technique builds on the successes of conventional liquid scintillator technology but also gives rise to new advantages. For example, its ability to image events down to the MeV scale gives it an unprecedented power to reject backgrounds. LiquidO also possesses an unparalleled ability for doping compared to conventional scintillator detectors, which are typically limited by transparency requirements. A small prototype has been used to validate the principles behind LiquidO's approach, which could find a wide range of applications in neutrino physics from the MeV to the GeV scale.

The LiquidO Concept

LiquidO is a new approach to detecting neutrinos that, in stark contrast with conventional liquid scintillator detectors, relies on using an opaque scintillator medium as the primary neutrino target. The scintillators that can be best used by LiquidO have a short scattering length and a medium to long absorption length, an example of which has already been successfully produced [1]. In such a medium, the photons produced by the opaque scintillator undergo a random walk process near their creation point and are trapped in so-called *light balls* around each energy deposition point. The light is collected by a dense array of wavelength-shifting fibres that traverses the volume and that is readout by photo-sensors in the periphery. Silicon photomultipliers (SiPMs) are well-suited to this purpose given their affordable price, high efficiency, and excellent time resolution.

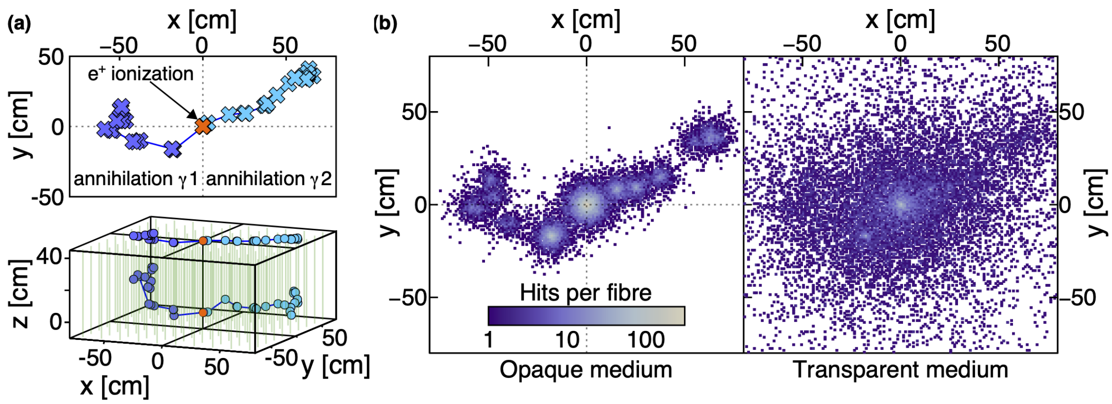

FIG. 1. Left: energy depositions of a simulated 1 MeV positron in a LiquidO detector with a regular 1 cm fibre pitch running along the z direction. The fibres are represented in green. Right: true number of photons hitting the fibres, each of which is represented by a pixel, in the opaque and transparent scintillator scenarios. In the former case, the scintillator is assumed to have a 5 mm scattering length and a 5 m absorption length. Figure obtained from Ref. [2].

A full description of LiquidO, its expected performance, first experimental demonstration, and potential applications, can be found in Ref. [2]. Fig. 1 illustrates LiquidO's performance using a simulated 1 MeV positron. Here, the simplest configuration with fibres running only along one direction (z) is assumed. The true energy depositions of the positron are shown on the left panel (a), and the number of true photons hitting each fibre on the right panel (b). The positron's loss of kinetic energy produces a light-ball at the vertex of the event. The two back-to-back gamma-rays resulting from its annihilation lose energy via Compton scattering, leaving two trails of smaller light balls that detach from the central one. A comparison is made in panel (b) of the light pattern collected by the fibre array when using an opaque versus a transparent scintillator. Despite the use of fibres, the event topology is almost entirely washed out in the latter case, illustrating the key role played by the scintillator's opacity in self-segmenting the detector.

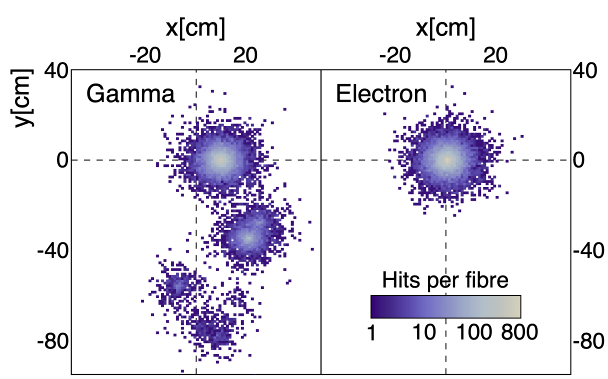

FIG. 2. Simulated 2 MeV gamma (left) and electron (right) in the same detector configuration of Fig. 1. Figure obtained from Ref. [2].

The clear event topology of ~MeV positrons in LiquidO stands in contrast with that of other events, as illustrated in Fig. 2. At these energies, gammas lose their energy primarily via the Compton effect and produce trails of light balls, whereas electrons produce single light balls. At higher energies (more than

$\sim$10 MeV for electrons), charged particles have enough kinetic energy to travel several cm or more in the detector, producing sequences of point-like energy depositions that form clear tracks. As a result, many other interactions, from cosmic ray muons to charged and neutral current neutrino interactions of various energies, could also be precisely reconstructed in LiquidO.

LiquidO's Advantages

LiquidO builds on the decades-long experience with liquid scintillator detectors and inherits some of their main advantages, such as the relatively high light levels compared to other technologies. Estimating the total photon detection efficiency at 3%, which is dominated by the $\sim$10% probability that a photon re-emitted by the wavelength-shifting fibres is trapped and carried to the SiPMs [3], and assuming a scintillator with conventional light-yield and absorption length like the one of Ref. [1], yields 400 photo-electrons per MeV for a small 1 cm-pitch lattice detector. When scaling to larger sizes this amount is reduced due to the several-meter attenuation length of wavelength-shifting fibres.

LiquidO also brings new advantages to the table, two of which in particular could unlock new opportunities in neutrino physics:

- **Unprecedented background rejection**: LiquidO's unique imaging capabilities enable unprecedented event-by-event identification down to the MeV scale. For example, assuming a total detection efficiency of 3%, and using a very simple reconstruction relying solely on the spatial spread of the hit fibres, it is estimated that 2 MeV electrons can be separated from gammas with a contamination better than 10^{-2} [2].
- **Naturally enhanced affinity for doping**: maintaining the required transparency of the scintillator typically limits the doping concentrations that can be achieved in conventional liquid scintillator detectors. In contrast, LiquidO requires opacity to confine the light and therefore allows for more possibilities, be it to load new materials or to achieve significantly higher levels of doping.

Possible Applications and Status

LiquidO could find a wide range of applications within neutrino physics. Thanks to its strong separation power between positrons and electrons, LiquidO would greatly reduce the cosmogenic backgrounds in experiments detecting antineutrinos via the Inverse Beta Decay reaction ($\bar{\nu}_e + p \to e^+ + n$), which typically bear the brunt of the systematic uncertainty. Similarly, LiquidO's self-segmenting effectively keeps events localized, allowing the detector to tolerate much higher rates. This means that a major reduction of the overburden, shielding, and buffer requirements would be possible. In fact, this feature makes LiquidO a promising technology to monitor reactor antineutrinos for non-proliferation purposes [4].

Moreover, the ability to dope a LiquidO detector with various elements at concentrations that would be prohibitive in conventional detectors could enable new measurements from a variety of sources that include the sun, supernovae, pion decay-at-rest beams, and radioactive elements. Using Indium in a LiquidO detector, for instance, could enable pp solar neutrino spectroscopy with a threshold of 114 keV via the $\nu_e + {}^{115}\text{In} \to e^- + {}^{115}\text{Sn}^*$ reaction proposed by Raghavan [5]. The electron signal, followed by the decay of the tin nucleus, would provide a powerfully distinct signature. Similarly, the ability to control backgrounds, and to dope the scintillator with elements like Telurium well beyond current limits, could result in a state-of-the-art detector to search for neutrinoless double-beta decay. Some of these possibilities and others are discussed in more detail in Ref. [2].

The basic principles behind LiquidO have already been validated with a small detector prototype filled with a scintillator whose opacity changes with temperature [1] and exposed to a mono-energetic 1 MeV e^- source [6]. The results unmistakably showed that, as the scintillator's scattering length decreased, light was confined near the beam's energy deposition point, as expected. The details can be found in Ref. [2]. Further studies are ongoing with a larger prototype, and the results will be released in the near future.

---

[1] C. Buck, B. Gramlich, and S. Schoppmann, Novel Opaque Scintillator for Neutrino Detection, JINST **14** (11), P11007, arXiv:1908.03334 [physics.ins-det].

[2] A. Cabrera *et al.*, Neutrino Physics with an Opaque Detector (2019), arXiv:1908.02859 [physics.ins-det].

[3] J. D. Weiss, Trapping efficiency of fluorescent optical fibers, Optical Engineering **54**, 1 (2015).

[4] P. Huber and T. Schwetz, Precision spectroscopy with reactor anti-neutrinos, Phys. Rev. **D70**, 053011 (2004), arXiv:hep-ph/0407026 [hep-ph].

[5] R. S. Raghavan, Inverse beta decay of 115-In to 115-Sn*: a new possibility for detecting solar neutrinos from the proton-proton reaction, Phys. Rev. Lett. **37**, 259 (1976).

[6] C. Marquet *et al.*, High energy resolution electron beam spectrometer in the MeV range, JINST **10** (09), P09008.

Authors:

A. Abusleme,[1] J. dos Anjos,[2,*] T. J. C. Bezerra,[3] M. Bongrand,[4] C. Bourgeois,[4] D. Breton,[4] C. Buck,[5] J. Busto,[6] A. Cabrera,[7,4,8] E. Calvo,[9] E. Chauveau,[10] M. Chen,[11] P. Chimenti,[12] F. Dal Corso,[13] G. De Conto,[12] S. Dusini,[13] G. Fiorentini,[14,15] C. Frigerio Martins,[12] A. Givaudan,[7] P. Govoni,[16,17] B. Gramlich,[5] M. Grassi,[7,4,18] Y. Han,[7,4] J. Hartnell,[19] C. Hugon,[6] S. Jiménez,[9] H. de Kerret,[7,†] A. Le Nevé,[4] P. Loaiza,[4] J. Maalmi,[4] F. Mantovani,[14,15] L. Manzanillas,[4] C. Marquet,[10] J. Martino,[3] D. Navas-Nicolás,[4,9] H. Nunokawa,[20] M. Obolensky,[7] J. P. Ochoa-Ricoux,[21] G. Ortona,[22] C. Palomares,[9] F. Pessina,[20] A. Pin,[10] J. C. C. Porter,[19] M. S. Pravikoff,[10] M. Roche,[10] B. Roskovec,[21] N. Roy,[4] C. Santos,[7] A. Serafini,[14,15] L. Simard,[4] M. Sisti,[16] L. Stanco,[13] V. Strati,[14,15] J.-S. Stutzmann,[3] F. Suekane,[7,23] A. Verdugo,[9] B. Viaud,[3] C. Volpe,[7] C. Vrignon,[7] S. Wagner,[7] and F. Yermia[3]

[1]*Pontificia Universidad Católica de Chile, Santiago, Chile*

[2]*Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, RJ, 22290-180, Brazil*

[3]*SUBATECH, CNRS/IN2P3, Université de Nantes, IMT-Atlantique, 44307 Nantes, France*

[4]*LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France*

[5]*Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany*

[6]*Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France*

[7]*APC, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, Sorbonne Paris Cité University, 75205 Paris Cedex 13, France*

[8]*LNCA Underground Laboratory, CNRS/IN2P3 - CEA, Chooz, France*

[9]*CIEMAT, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), E-28040 Madrid, Spain*

[10]*Université de Bordeaux, CNRS, CENBG-IN2P3, F-33170 Gradignan, France*

[11]*Department of Physics, Engineering Physics & Astronomy, Queen's University, Kingston, Ontario K7L3N6, Canada*

[12]*Departamento de Física, Universidade Estadual de Londrina, 86051-990, Londrina – PR, Brazil*

[13]*INFN, Sezione di Padova, via Marzolo 8, I-35131 Padova, Italy*

[14]*INFN, Ferrara Section, Via Saragat 1, 44122 Ferrara, Italy*

[15]*Department of Physics and Earth Sciences, University of Ferrara, Via Saragat 1, 44122 Ferrara, Italy*

[16]*INFN, Sezione di Milano-Bicocca, I-20126 Milano, Italy*

[17]*Università di Milano-Bicocca, I-20126 Milano, Italy*

[18]*Dipartimento di Fisica e Astronomia, Università di Padova, Via Marzolo 8 , I-35131 Padova, Italy*

[19]*Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, United Kingdom*

[20]*Department of Physics, Pontifícia Universidade Católica do Rio de Janeiro, Rio de Janeiro, RJ, 22451-900, Brazil*

[21]*Department of Physics and Astronomy, University of California at Irvine, Irvine, California 92697, USA*

[22]*INFN, Sezione di Torino, I-10125 Torino, Italy*

[23]*RCNS, Tohoku University, 6-3 AzaAoba, Aramaki, Aoba-ku, 980-8578, Sendai, Japan*

[*] Also at Observatório Nacional. Rio de Janeiro, Brasil

[†] Deceased.