Water-Based Liquid Scintillators

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Monolithic optical detectors, either water–Cherenkov detectors or liquid scintillator detectors, are a well-established technique in neutrino physics. Using water-based liquid scintillators (WbLS) is an approach that exploits Cherenkov and scintillation signals simultaneously; i.e., water is loaded with 1% to 10% liquid scintillator.

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1. Introduction

Organic liquid scintillators have been a key technology in the field of neutrino physics for decades. They are especially suited for low-energy neutrino applications due to their high light output and proportional response to the incident particle energy. The first experiment to successfully detect neutrinos already used a liquid scintillator in 1956 [1]. Since then, they have been used in numerous detectors due to their high purity, low energy threshold, volume flexibility and scalability, low costs, and homogeneity.

In the field of neutrino physics and related fields of research, organic liquid scintillators have allowed for several measurements and discoveries. These include the understanding of neutrino flavor mixing and oscillations through long baseline observations by KamLAND [2] and NOvA [3], as well as short baseline observations from Daya Bay [4], Double Chooz [5], and RENO [6]. KamLAND [7] and later Borexino [8] were able to detect geoneutrinos from Earth. Solar neutrinos detected in Borexino allowed insights into our sun [9][10]. Organic liquid scintillator detectors such as the accelerator-based LSND [11] and the very-short-baseline reactor-based experiments NEOS [12], STEREO [13], PROSPECT [14], and Neutrino-4 [15], investigated indications for additional sterile neutrino states, which are currently under dispute [16][17]. Furthermore, at a very short baseline, nuclear reactor monitoring was achieved by the Nucifer detector [18] using an organic liquid scintillator.

Upcoming organic liquid scintillator detectors, including JUNO [19], Theia [20], KAMland-ZEN [21], SNO+ [22], and Prospect-II [23], can give further insight into our Sun and Earth, supernovae, the Majorana character of neutrinos, neutrino masses, and the existence of additional sterile neutrinos, and allow for improved reactor monitoring [24][25][26].

To allow for such discoveries, various ideas on the advancement of organic liquid scintillators have been developed in recent years. They mostly target the improvement of individual aspects of organic liquid scintillators by the introduction of new materials into the scintillator or combining the scintillator with other materials. These aspects include improvements to the directional resolution, vertex resolution, particle identification, light yield, metal loading, safety, and radiopurity. While recent developments show promising progress in terms of directional resolution and particle identification with traditional organic liquid scintillators [27][28], the new ideas seek to outperform these achievements. Based on several of those ideas, experimental collaborations have been formed to demonstrate and advance suitable detectors and investigate the performance and discovery potential of these new technologies.

2. Water-Based Liquid Scintillators

Monolithic optical detectors, either water–Cherenkov detectors or liquid scintillator detectors, are a well-established technique in neutrino physics. Using water-based liquid scintillators (WbLS) is an approach that exploits Cherenkov and scintillation signals simultaneously; i.e., water is loaded with 1% to 10% liquid scintillator [29][30][31][32]. The approach is similar to previously used highly diluted organic scintillators [33][34] or an approach using slow scintillators. However, since water is the main component in WbLS, the WbLS approach offers benefits such as low costs and strongly reduced fire and environmental hazards. The WbLS technology is foreseen in the Eos and ANNIE experiments [35][36] and could be deployed in planned experiments such as AIT-NEO, Theia, and beyond [20][37][38] or in the context of medical particle-beam therapy [39]. The technology is expected to allow improvements in many fields, such as high-energy, nuclear, geo-, and astrophysics such as neutrino mass ordering, CP violation in the leptonic sector, solar neutrinos, diffuse supernova neutrinos, neutrinos from supernova bursts, neutrinos from the Earth's crust, nucleon decay, and neutrinoless double beta decay with sensitivity towards normal neutrino mass ordering [40][41][42][43][44].

In a water-based liquid scintillator detector, it is possible to use the Cherenkov signals to provide directional and topological information while maintaining the good energy resolution of liquid scintillators. This separation between Cherenkov and scintillation light has been demonstrated in the CHESS setup [45][46]. Water-based liquid scintillators are expected to have good particle-identification capabilities (PID) following a discrimination strategy based on the particle-dependent Cherenkov/scintillation light ratio. This PID can improve the discrimination of alpha/beta particles and might allow some discrimination of beta/gamma particles. The PID performance of WbLS will be investigated by Eos [35]. It arises from two sources: the time profile of scintillation light emitted due to a recoiling proton may differ from electron-like events due to quenching effects, and the ratio of Cherenkov to scintillation light differs between heavier and lighter particles. Additionally, recent developments have demonstrated the capability to identify neutron/gamma particles through the pulse shape discrimination of the scintillation light [47]. Another additional benefit exists with respect to metal loading. In WbLS, loading can happen in the aqueous phase, which is easier to achieve than the direct loading of the organic scintillator.

The separation of Cherenkov and scintillation light signals can be achieved by two means. One idea is to separate fast-Cherenkov and slow-scintillation light time-wise [48]. This is in particular achieved via fast photon detectors, e.g., a Large Area Picosecond Photo-Detector (LAPPD™) [49][50][51]. Another idea is spectral separation between long-wavelength photons, which are dominated by the Cherenkov light, and short-wavelength photons, which can be – dependent on the scintillator fraction in the detector medium – dominated by scintillation light. Here, photodetectors with strong wavelength-dependent efficiency or dichroicons, Winston-cone-style light concentrators built out of dichroic reflectors, can be used [52][53].

Organic solvents, as used in liquid scintillators, are immiscible with water. This is mainly caused by the differences in the polarities of the molecules. To produce water-based liquid scintillators, the hydrophobic (lipophilic) scintillator component has to be brought into a stable suspension with the hydrophilic (lipophobic) water phase. An ampliphilic surface-active agent (surfactant) consisting of molecules with lypophilic and hydrophilic groups can be used to emulsify the organic solvent into the water solvent by reducing the tension between the organic solvent and the water [54]. The degree of tension reduction depends on the concentration of the surfactant. Its concentration can in turn also affect the optical and stability properties of the medium. A typical surfactant molecule possesses hydrophilic groups on one end and hydrophilic groups at the opposite end of the molecule. They can therefore form a hydrophilic shell around a hydrophobic droplet of scintillator inside the water, a so-called micelle. Micelles of large size can cause substantial translucence. Likewise, a high concentration of micelles can give rise to opacity.

Early studies investigated the possibility of producing water-based liquid scintillators from linear-alkyl-benzene-sulfonate (LAS), a derivate of the well-known linear-alkyl-benzene (LAB) [29]. Its light yield was found to have a dependence on the scintillator concentration of (127.9 ± 17.0) photons/MeV/%LS and an intercept value of (108.3 ± 51.0) photons/MeV, indicating a non-linear behavior at low concentrations [55]. For scintillator fractions between 1% and 10% in water, a clear dominance of Cherenkov light over scintillation light in the rising part of the light pulse could be seen in a fit of the data. From about 5% loading upwards, the fraction of scintillation light starts to dominate the peak of the pulse by more than an order of magnitude. A measurement of the relative proton light yield of a 5% WbLS showed it to be approximately 3.8% lower than that of a pure LAB+2,5-diphenyloxazole (PPO) reference [56].

An alternative approach to WbLS uses 13% Triton™X-100 as surfactant combined with 86% water and 1% LAB including 100 g/L PPO, as well as 10 mg/L vitamin C for pH control [32]. Here, a light yield of about (198 ± 5) photons/MeV is reported. The distribution of the sizes of micelles peaks at 2.8 nm. An important step in the production is the filtering of the WbLS, typically at the order of 10 nm to 100 nm.

References

1. Cowan, C.L.; Reines, F.; Harrison, F.B.; Kruse, H.W.; McGuire, A.D. Detection of the Free Neutrino: A Confirmation. Science 1956, 124, 103–104.
2. Abe, S.; Ebihara, T.; Enomoto, S.; Furuno, K.; Gando, Y.; Ichimura, K.; Ikeda, H.; Inoue, K.; Kibe, Y.; Kishimoto, Y.; et al. Precision Measurement of Neutrino Oscillation Parameters with KamLAND. Phys. Rev. Lett. 2008, 100, 221803.
3. Acero, M.A.; Adamson, P.; Aliaga, L.; Alion, T.; Allakhverdian, V.; Altakarli, S.; Anfimov, N.; Antoshkin, A.; Aurisano, A.; Back, A.; et al. First measurement of neutrino oscillation parameters

using neutrinos and antineutrinos by NOvA. Phys. Rev. Lett. 2019, 123, 151803.

4. An, F.P.; Bai, J.Z.; Balantekin, A.B.; Band, H.R.; Beavis, D.; Beriguete, W.; Bishai, M.; Blyth, S.; Boddy, K.; Brown, R.L.; et al. Observation of Electron-Antineutrino Disappearance at Daya Bay. Phys. Rev. Lett. 2012, 108, 171803.
5. de Kerret, H.; Abrahao, T.; Almazan, H.; dos Anjos, J.C.; Appel, S.; Barriere, J.C.; Yermia, F. Double Chooz θ13 measurement via total neutron capture detection. Nat. Phys. 2020, 16, 558–564.
6. Ahn, J.K.; Chebotaryov, S.; Choi, J.H.; Choi, S.; Choi, W.; Choi, Y.; Jang, H.I.; Jang, J.S.; Jeon, E.J.; Jeong, I.S.; et al. Observation of Reactor Electron Antineutrinos Disappearance in the RENO Experiment. Phys. Rev. Lett. 2012, 108, 191802.
7. Araki, T.; Enomoto, S.; Furuno, K.; Gando, Y.; Ichimura, K.; Ikeda, H.; Piquemal, F. Experimental investigation of geologically produced antineutrinos with KamLAND. Nature 2005, 436, 499–503.
8. Agostini, M.; Altenmüller, K.; Appel, S.; Atroshchenko, V.; Bagdasarian, Z.; Basilico, D.; Bellini, G.; Benziger, J.; Bick, D.; Bonfini, G.; et al. Comprehensive geoneutrino analysis with Borexino. Phys. Rev. D 2020, 101, 012009.
9. Bellini, G.; Benziger, J.; Bick, D.; Bonfini, G.; Bravo, D.; Buizza Avanzini, M.; Caccianiga, B.; Cadonati, L.; Calaprice, F.; Cavalcante, P.; et al. Final results of Borexino Phase-I on low-energy solar neutrino spectroscopy. Phys. Rev. D 2014, 89, 112007.
10. The Borexino Collaboration. Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun. Nature 2020, 587, 577–582.
11. Athanassopoulos, C.; Auerbach, L.B.; Burman, R.L.; Cohen, I.; Caldwell, D.O.; Dieterle, B.D.; Donahue, J.B.; Eisner, A.M.; Fazely, A.; Federspiel, F.J.; et al. Evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ Oscillations from the LSND Experiment at the Los Alamos Meson Physics Facility. Phys. Rev. Lett. 1996, 77, 3082–3085.
12. Ko, Y.J.; Kim, B.R.; Kim, J.Y.; Han, B.Y.; Jang, C.H.; Jeon, E.J.; Joo, K.K.; Kim, H.J.; Kim, H.S.; Kim, Y.D.; et al. Sterile Neutrino Search at the NEOS Experiment. Phys. Rev. Lett. 2017, 118, 121802.
13. Almazán, H.; Bernard, L.; Blanchet, A.; Bonhomme, A.; Buck, C.; del Amo Sanchez, P.; El Atmani, I.; Haser, J.; Kandzia, F.; Kox, S.; et al. Improved sterile neutrino constraints from the STEREO experiment with 179 days of reactor-on data. Phys. Rev. D 2020, 102, 052002.
14. Andriamirado, M.; Balantekin, A.B.; Band, H.R.; Bass, C.D.; Bergeron, D.E.; Berish, D.; Bowden, N.S.; Brodsky, J.P.; Bryan, C.D.; Classen, T.; et al. Improved short-baseline neutrino oscillation search and energy spectrum measurement with the PROSPECT experiment at HFIR. Phys. Rev. D 2021, 103, 032001.

15. Serebrov, A.P.; Samoilov, R.M.; Ivochkin, V.G.; Fomin, A.K.; Zinoviev, V.G.; Neustroev, P.V.; Golovtsov, V.L.; Volkov, S.S.; Chernyj, A.V.; Zherebtsov, O.M.; et al. Search for sterile neutrinos with the Neutrino-4 experiment and measurement results. Phys. Rev. D 2021, 104, 032003.
16. Böser, S.; Buck, C.; Giunti, C.; Lesgourgues, J.; Ludhova, L.; Mertens, S.; Schukraft, A.; Wurm, M. Status of light sterile neutrino searches. Prog. Part. Nucl. Phys. 2020, 111, 103736.
17. Schoppmann, S. Status of Anomalies and Sterile Neutrino Searches at Nuclear Reactors. Universe 2021, 7, 360.
18. Boireau, G.; Bouvet, L.; Collin, A.P.; Coulloux, G.; Cribier, M.; Deschamp, H.; Durand, V.; Fechner, M.; Fischer, V.; Gaffiot, J.; et al. Online monitoring of the Osiris reactor with the Nucifer neutrino detector. Phys. Rev. D 2016, 93, 112006.
19. Abusleme, A.; Adam, T.; Ahmad, S.; Aiello, S.; Akram, M.; Ali, N.; An, F.; An, G.; An, Q.; Andronico, G.; et al. Feasibility and physics potential of detecting B-8 solar neutrinos at JUNO. Chin. Phys. C 2021, 45, 023004.
20. Askins, M.; Bagdasarian, Z.; Barros, N.; Beier, E.W.; Blucher, E.; Bonventre, R.; Zuber, K. THEIA: An advanced optical neutrino detector. Eur. Phys. J. C 2020, 80, 416.
21. Gando, A.; Gando, Y.; Hachiya, T.; Ha Minh, M.; Hayashida, S.; Honda, Y.; Hosokawa, K.; Ikeda, H.; Inoue, K.; Ishidoshiro, K.; et al. Precision Analysis of the 136Xe Two-Neutrino ββ Spectrum in KamLAND-Zen and Its Impact on the Quenching of Nuclear Matrix Elements. Phys. Rev. Lett. 2019, 122, 192501.
22. Albanese, V.; Alves, R.; Anderson, M.; Andringa, S.; Anselmo, L.; Arushanova, E.; Asahi, S.; Askins, M.; Auty, D.; Back, A.; et al. The SNO+ experiment. J. Instrum. 2021, 16, P08059.
23. Andriamirado, M.; Balantekin, A.B.; Band, H.R.; Bass, C.D.; Bergeron, D.E.; Bowden, N.S.; Bryan, C.D.; Carr, R.; Classen, T.; Conant, A.J.; et al. PROSPECT-II physics opportunities. J. Phys. G Nucl. Part. Phys. 2022, 49, 070501.
24. Akindele, T.; Anderson, T.; Anderssen, E.; Askins, M.; Bohles, M.; Bacon, A.J.; Bagdasarian, Z.; Baldoni, A.; Barna, A.; Barros, N.; et al. A Call to Arms Control: Synergies between Nonproliferation Applications of Neutrino Detectors and Large-Scale Fundamental Neutrino Physics Experiments. arXiv 2022, arXiv:2203.00042.
25. Akindele, O.A.; Berryman, J.M.; Bowden, N.S.; Carr, R.; Conant, A.J.; Huber, P.; Langford, T.J.; Link, J.M.; Littlejohn, B.R.; Fernandez-Moroni, G.; et al. High Energy Physics Opportunities Using Reactor Antineutrinos. arXiv 2022, arXiv:2203.07214.
26. Orebi Gann, G.D.; Zuber, K.; Bemmerer, D.; Serenelli, A. The Future of Solar Neutrinos. Annu. Rev. Nucl. Part. Sci. 2021, 71, 491–528.
27. Galbiati, C.; Misiaszek, M.; Rossi, N. α/β discrimination in Borexino. Eur. Phys. J. A 2016, 52, 86.

28. Agostini, M.; Altenmüller, K.; Appel, S.; Atroshchenko, V.; Bagdasarian, Z.; Basilico, D.; Bellini, G.; Benziger, J.; Biondi, R.; Bravo, D.; et al. First Directional Measurement of Sub-MeV Solar Neutrinos with Borexino. Phys. Rev. Lett. 2022, 128, 091803.
29. Yeh, M.; Hans, S.; Beriguete, W.; Rosero, R.; Hu, L.; Hahn, R.; Diwan, M.; Jaffe, D.; Kettell, S.; Littenberg, L. A new water-based liquid scintillator and potential applications. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip. 2011, 660, 51–56.
30. Bignell, L.; Beznosko, D.; Diwan, M.; Hans, S.; Jaffe, D.; Kettell, S.; Rosero, R.; Themann, H.; Viren, B.; Worcester, E.; et al. Characterization and modeling of a Water-based Liquid Scintillator. J. Instrum. 2015, 10, P12009.
31. Onken, D.R.; Moretti, F.; Caravaca, J.; Yeh, M.; Orebi Gann, G.D.; Bourret, E.D. Time response of water-based liquid scintillator from X-ray excitation. Mater. Adv. 2020, 1, 71–76.
32. Steiger, H.T.J.; Böhles, M.; Dörflinger, D.; Fahrendholz, U.; Guffanti, D.; Mpoukouvalas, A.; Oberauer, L.; Steiger, A.; Stock, M.R.; Wurm, M.; et al. Development, Characterization and Production of a novel Water-based Liquid Scintillator based on the Surfactant TRITON™X-100. J. Instrum. 2023; in press.
33. Reeder, R.; Dieterle, B.; Gregory, C.; Schaefer, F.; Schum, K.; Strossman, W.; Smith, D.; Christofek, L.; Johnston, K.; Louis, W.; et al. Dilute scintillators for large-volume tracking detectors. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip. 1993, 334, 353–366.
34. Athanassopoulos, C.; Auerbach, L.; Bauer, D.; Bolton, R.; Burman, R.; Cohen, I.; Caldwell, D.; Dieterle, B.; Donahue, J.; Eisner, A.; et al. The liquid scintillator neutrino detector and LAMPF neutrino source. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip. 1997, 388, 149–172.
35. Anderson, T.; Anderssen, E.; Askins, M.; Bacon, A.J.; Bagdasarian, Z.; Baldoni, A.; Barros, N.; Bartoszek, L.; Bergevin, M.; Bernstein, A.; et al. EOS: A demonstrator of hybrid optical detector technology. arXiv 2022, arXiv:2211.11969.
36. Anghel, I.; Beacom, J.F.; Bergevin, M.; Blanco, C.; Catano-Mur, E.; Di Lodovico, F.; Yeh, M. Letter of Intent: The Accelerator Neutrino Neutron Interaction Experiment (ANNIE). arXiv 2015, arXiv:1504.01480.
37. Askins, M.; Bergevin, M.; Bernstein, A.; Dazeley, S.; Dye, S.T.; Handler, T.; Hatzikoutelis, A.; Hellfeld, D.; Jaffke, P.; Kamyshkov, Y.; et al. The Physics and Nuclear Nonproliferation Goals of WATCHMAN: A WAter CHerenkov Monitor for ANtineutrinos. arXiv 2015, arXiv:1502.01132.
38. Fischer, V.; Tiras, E. Water-based Liquid Scintillator detector as a new technology testbed for neutrino studies in Turkey. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip. 2020, 969, 163931.

39. Bignell, L.; Diwan, M.; Hans, S.; Jaffe, D.; Rosero, R.; Vigdor, S.; Viren, B.; Worcester, E.; Yeh, M.; Zhang, C. Measurement of radiation damage of water-based liquid scintillator and liquid scintillator. J. Instrum. 2015, 10, P10027.
40. Sawatzki, J.; Wurm, M.; Kresse, D. Detecting the diffuse supernova neutrino background in the future water-based liquid scintillator detector Theia. Phys. Rev. D 2021, 103, 023021.
41. Bat, A.; Tiras, E.; Fischer, V.; Kamislioglu, M. Low Energy Neutrino Detection with a Portable Water-based Liquid Scintillator Detector. arXiv 2021, arXiv:2112.03418.
42. Land, B.; Bagdasarian, Z.; Caravaca, J.; Smiley, M.; Yeh, M.; Orebi Gann, G. MeV-scale performance of water-based and pure liquid scintillator detectors. Phys. Rev. D 2021, 103, 052004.
43. Zsoldos, S.; Bagdasarian, Z.; Orebi Gann, G.D.; Barna, A.; Dye, S. Antineutrino sensitivity at THEIA. arXiv 2022, arXiv:2204.12278.
44. Bonventre, R.; Orebi Gann, G.D. Sensitivity of a low threshold directional detector to CNO-cycle solar neutrinos. Eur. Phys. J. C 2018, 78, 435.
45. Caravaca, J.; Descamps, F.B.; Land, B.J.; Wallig, J.; Yeh, M.; Orebi Gann, G.D. Experiment to demonstrate separation of Cherenkov and scintillation signals. Phys. Rev. C 2017, 95, 055801.
46. Caravaca, J.; Descamps, F.B.; Land, B.J.; Yeh, M.; Orebi Gann, G.D. Cherenkov and Scintillation Light Separation in Organic Liquid Scintillators. Eur. Phys. J. C 2017, 77, 811.
47. Ford, M.J.; Zaitseva, N.P.; Carman, M.L.; Dazeley, S.A.; Bernstein, A.; Glenn, A.; Akindele, O.A. Pulse-shape discrimination in water-based scintillators. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip. 2022, 1036, 166854.
48. Aberle, C.; Elagin, A.; Frisch, H.J.; Wetstein, M.; Winslow, L. Measuring directionality in double-beta decay and neutrino interactions with kiloton-scale scintillation detectors. J. Instrum. 2014, 9, P06012.
49. Lyashenko, A.V.; Adams, B.W.; Aviles, M.; Cremer, T.; Ertley, C.D.; Foley, M.R.; Spieglan, E. Performance of Large Area Picosecond Photo-Detectors (LAPPD™). Nucl. Instrum. Meth. A 2020, 958, 162834.
50. Minot, M.; Adams, B.; Aviles, M.; Bond, J.; Cremer, T.; Foley, M.; Lyashenko, A.; Popecki, M.; Stochaj, M.; Worstell, W.; et al. Large Area Picosecond Photodetector (LAPPD™)—Pilot production and development status. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip. 2019, 936, 527–531.
51. Kaptanoglu, T.; Callaghan, E.J.; Yeh, M.; Orebi Gann, G.D. Cherenkov and scintillation separation in water-based liquid scintillator using an LAPPD™. Eur. Phys. J. C 2022, 82, 169.

52. Kaptanoglu, T.; Luo, M.; Klein, J. Cherenkov and Scintillation Light Separation Using Wavelength in LAB Based Liquid Scintillator. J. Instrum. 2019, 14, T05001.
53. Kaptanoglu, T.; Luo, M.; Land, B.; Bacon, A.; Klein, J.R. Spectral photon sorting for large-scale Cherenkov and scintillation detectors. Phys. Rev. D 2020, 101, 072002.
54. Choi, J.W.; Choi, J.Y.; Joo, K.K.; Woo, H.J. Development of water-based liquid scintillator based on hydrophilic-lipophilic balance index. Phys. Scr. 2022, 97, 045304.
55. Caravaca, J.; Land, B.J.; Yeh, M.; Orebi Gann, G.D. Characterization of water-based liquid scintillator for Cherenkov and scintillation separation. Eur. Phys. J. C 2020, 80, 867.
56. Callaghan, E.J.; Goldblum, B.L.; Brown, J.A.; Laplace, T.A.; Manfredi, J.J.; Yeh, M.; Orebi Gann, G.D. Measurement of proton light yield of water-based liquid scintillator. arXiv 2022, arXiv:2210.03876.