Low-Threshold Scintillation Detector Development for Dark Matter and Neutrino

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Abstract

It is still one of the main directions to search for dark matter with better sensitivity and to measure neutrinos with good statistics and better precision. The technologies of scintillation detectors on the low-threshold, low background, and good directionality are valuable and can contribute to the study. In this topic, I will try to introduce some progress on the development of the low threshold scintillation detector for dark matter and neutrino in liquid argon (LAr) and liquid scintillator (LS) and make some review on interesting topics.

Keywords: scintillation detector, low threshold, dark matter, neutrino
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1. INTRODUCTION

Dark matter constitutes around 85% of the matter density and 26% of the total energy density of the universe. The nature of dark matter is one of the most exciting questions in science today [1]. Neutrinos, after their first detection in the 1960s, are used as a good way to probe different sources now and have to be a new and novel way of probing areas of solar physics, geophysics, and particle physics. Along with forming an important part of new fields like multimessenger astroparticle physics, neutrino physics also seeks to shed light on physical processes not described by the Standard Model [2, 3, 4].

As shown in Figure 1 of [5], the main technologies used for dark matter and neutrino detection can be classified into three categories: ionization, scintillation, and phonon or heat. The intrinsic threshold depends on different techniques [6, 7]: around 10 to 100 eV to generate a photon with an energy of 1 to 10 eV for scintillation, around 1 eV (semiconduct) to 10 eV (noble gas) to generate an iron pair for ionization, and around meV to generate a signal for phonon or heat (depends on heat capacitance). The scintillation detector (or combining with ionization) is much more convenient to realize a large detection target for statistics, which is selected by many experiments of dark matter and neutrino.

Weakly Interacting Massive Particles (WIMPs) are a generic class of dark matter candidates [8, 9] and may be detectable via weak-force-mediated nuclear recoils in detectors on Earth [10, 11, 12]. A WIMP could scatter elastically in targets of noble gases to produce a recoil in direct dark matter search experiments. As calculated energy spectrum in the left figure [7] of Figure 2 for electron scattering, the recoil energy can lower from sub-keV to tens eV. The right figure [13] of Figure 2 is the measured energy spectrum of Borexino [14], which had already an energy threshold of around 0.3 MeV for solar neutrino measurement.

In this note, some status and R&D jobs will be discussed for the low-threshold technologies aiming for dark matter and neutrino detection with scintillation detectors. Some dual-phase liquid argon work will be discussed in Section 2 after the introduction in Section 1. The detectors of the liquid scintillator of JUNO and JUNO-TAO will be reviewed in Section 3. And some new technologies will be discussed in Section 4.

2. DUAL-PHASE LAr

One of the typical dual-phase liquid argon (LAr) detectors is the Darkside project [15, 16], which had already reached a good measurement on backgrounds and low threshold for dark matter measurement. Figure 3 [17] shows around a 15 $\mathrm{keV_{nr}}$ threshold for dark matter measurement and background reduction after particle identification by scintillation timing with pulse shape technology [15, 18], which means around a 3 to 5 $\mathrm{keV_{ee}}$ threshold.

Following the design of a dual-phase LAr detector, a proposal, as in [19], is raised for the coherent elastic neutrino-nucleus scattering (CEνNS [20, 21, 22]) with reactor neutrinos from Taishan nuclear power plant, Guangdong, China, which is a work of our group. The design of the dual-phase LAr detector can be found on the left of Figure 4 [23]. It aims to measure the neutrino elastics scattering cross section with a better confidence level and check the parameters (such as θ_W, ϵ, and μ_ν) of the standard model with ton level target [24]. The design is trying to reach a sub-$\mathrm{keV_{ee}}$ or $\mathrm{keV_{nr}}$ energy threshold and single electron identification (threshold to four to 20 electrons). A small prototype detector [19] is realized as designed on the right of Figure 4. The dimension of the prototype is around 5 cm (height) $\times$ 8 cm (diameter) and 1.5 cm thickness of the gas layer, which is coupled with two 3-inch PMTs (R11065). The sensitive weight of air argon is around 0.35 Kg. The design will be dipped into a cryogenic system and filled with air argon.

The measured typical pulses can be found in Figure 5 [25, 26]. The signal from the dual-phase argon can be seen clearly: S1 from the liquid phase and S2 from the gas phase. As known, this is the typical feature of the dual-phase detector, which is also showing the prototype reached a working phase as a first step.

The detector is measured with an inside ^{241}Am source and surveyed with different electron drift field strengths and electroluminescence fields. The left figure [26] of Figure 6 shows the measured electron number per KeV of the prototype, which is around 11.5 electrons/KeV with a 300 V drift electronics field. The right figure of Figure 6 shows the measured light yield per

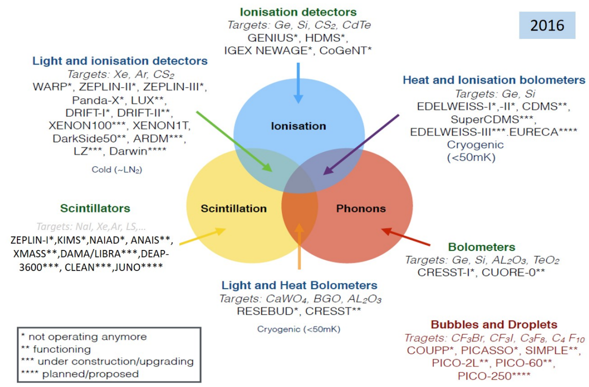


FIGURE 1: The typical technologies used for particle detection [5].

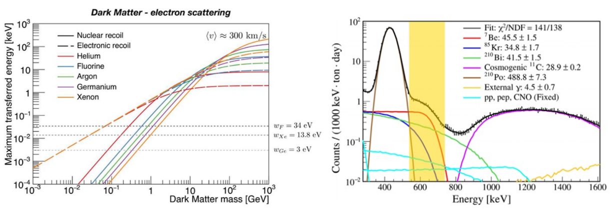


FIGURE 2: Left: energy of dark matter scattering with electron [7]. Right: solar neutrino measurement by Borexino [13].

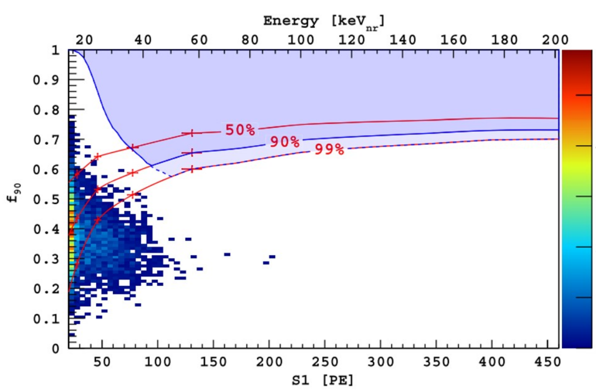


FIGURE 3: The measured low-energy events from Darkside-50 for dark matter [17], which has around a 15 keV$_{nr}$ threshold.

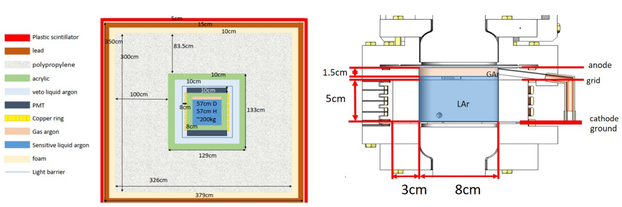


FIGURE 4: Left: the proposed detector structure including shielding for CEνNS in Taishan [19]. Right: the prototype detector structure for R&D measurement [23].

KeV of S1 of the prototype, which is around 7.4 photoelectron (p.e.)/KeV at maximum without drift electronics field. The measured light yield of S2 is around 20 p.e./e$^-$ with 6000 V electroluminescence field of the gas layer, which is similar to the reported light yield in argon-based detectors as [27]. It is confirmed that the purification system is also working properly to reach such a running phase.

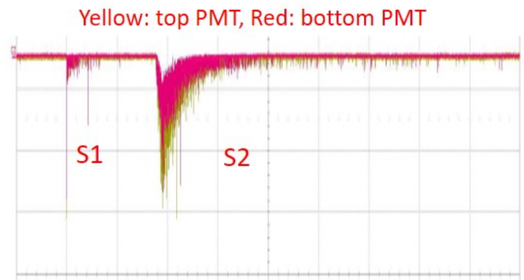


FIGURE 5: Typical pulses of the dual-phase argon prototype with S1 and S2 of the two PMTs [26].

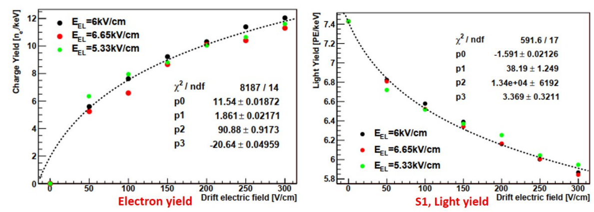


FIGURE 6: Left: the measured yield of electron of S1 versus different drift electronic fields. Right: the measured yield of light of S1 versus different drift electronic fields [26].

3. LIQUID SCINTILLATOR (LS) DETECTOR

There are lots of discussions about the liquid-based scintillator as in Figure 7 [28, 29], where the light yield, the attenuation length, particle identification ability, cost, stability, compatibility, and the safety factor are generally considered for the strategy selection of a detector.

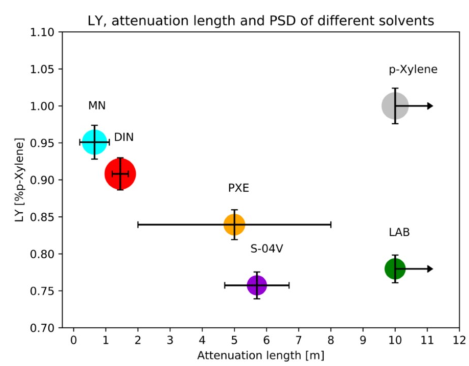


FIGURE 7: LS comparison of light yield versus attenuation length from [29].

Two typical LS detectors are under construction in China: JUNO [30] as shown on left of Figure 8 and JUNO-TAO [31] as shown on the right of Figure 8, which both are the work of our group. The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kton liquid scintillator detector in a laboratory at 700-meter underground. An excellent energy resolution and a large fiducial volume offer exciting opportunities for addressing many important topics in neutrino and astroparticle physics [32]. It expects a yield of 1345 photoelectrons per MeV by the design of the >20 m attenuation length of the liquid scintillator, excellent PMTs [33, 34] coverage and high detection efficiency, the transparency of the acrylic panel, etc.

The Taishan Antineutrino Observatory (TAO, also known as JUNO-TAO [31]) is a satellite experiment of JUNO. A ton-level liquid scintillator detector will place about 30 m from the core of the Taishan Nuclear Power Plant. A spherical acrylic vessel containing a 2.8-ton gadolinium-doped liquid scintillator will be viewed by around $10\,m^2$ Silicon Photomultipliers (SiPMs) of >50% photon detection efficiency with almost full coverage. The photoelectron yield is about 4500 per MeV, which is an order higher than any existing large-scale liquid scintillator detectors [35, 36] as Daya bay [37], KamLAND [38], Borexino [39]. The detector operates at $-50°C$ to lower the dark noise of SiPMs to an acceptable level. The detector will measure about 2000 reactor antineutrinos per day.

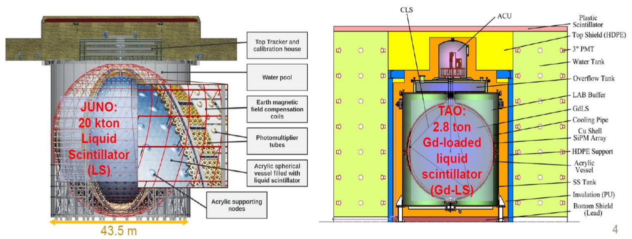


FIGURE 8: Left: JUNO detector design with a 20-kton LS coupled with PMTs under room temperature [32]. Right: JUNO-TAO detector design with a 2.8-kton Gd-loaded LS coupled with SiPM under $-50°C$ [31].

With the estimation of the contribution of radioactivity from different components and the cosmic-related background, the expected energy spectrum of JUNO can be simulated as shown in Figure 9 [4]. JUNO is trying to reach a threshold around 0.2 MeV with a kilo Hz trigger rate for possible solar neutrino measurements, which is mainly limited by the contribution of ^{11}C of the LS. The measurement of solar neutrino still depends on the cleanness control of the material and the installation process.

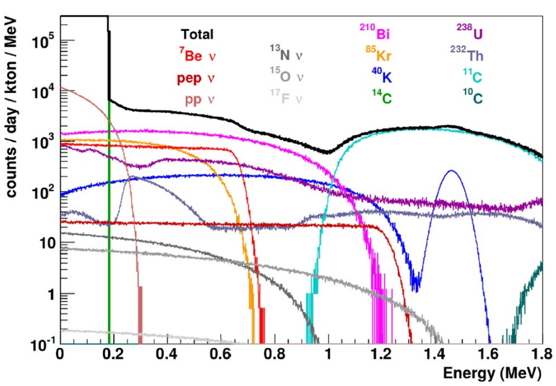


FIGURE 9: The simulated energy spectrum of JUNO with estimated radioactivity contributions [4].

4. OTHER NEW POSSIBILITIES

A new type of scintillating liquid based on water is used for a very large, but economical detector discussed in [40, 41]. The water-based liquid scintillator is already of great interest to large-scale physics experiments, e.g., nucleon decay, long baseline accelerator neutrinos, geoneutrino, etc., due to its relative simplicity of liquid handling and cost-efficiency. The properties of the target can be adjusted to the physics goals and offer additional options for metal loading as shown in Figure 10 [42]. Due to the mixture usage of water Cherenkov light and the scintillation light of the liquid scintillator, it can lower the Cherenkov energy threshold, so that a low-energy neutrino can be detected and reconstructed for vertex and tracks.

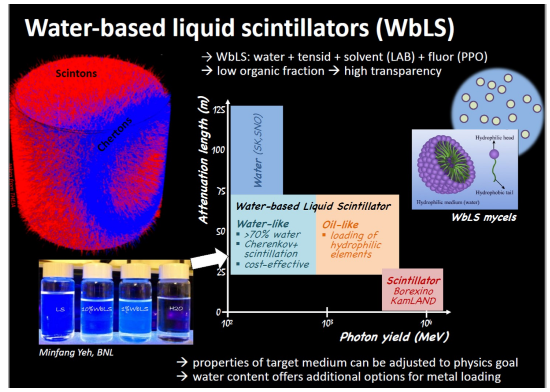
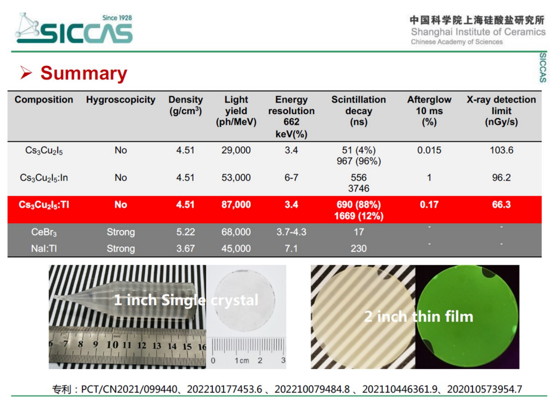


FIGURE 10: Water-based LS for direction reconstruction and better attenuation [42].

There are also R&D efforts on new Cs-Cu-I-based crystals as shown in Figure 11 [43]. The new type of crystal based on the Cs-Cu-I strategy has reached a light yield of around 87,000 photons/MeV and a peak wavelength of around 500 nm. Further understanding of measurements is still going on. Compared with the classical crystals based on NaI:Tl and CsI:Tl, the new strategy could have a comparable price of raw materials and preparation process, comparable density, lower afterglow, lower band gap, Tl-doping feasible, and ternary compound providing broader space for electronic band structure engineering. We are also cooperating with this R&D for possible further application in our group.



Composition	Hygroscopicity	Density (g/cm^3)	Light yield (ph/MeV)	Energy resolution 662 keV(%)	Scintillation decay (ns)	Afterglow 10 ms (%)	X-ray detection limit (nGy/s)
$Cs_3Cu_2I_5$	No	4.51	29,000	3.4	51 (4%) 967 (96%)	0.015	103.6
$Cs_3Cu_2I_5$:In	No	4.51	53,000	6-7	556 3746	1	96.2
$Cs_3Cu_2I_5$:Tl	No	4.51	87,000	3.4	690 (88%) 1669 (12%)	0.17	66.3
$CeBr_3$	Strong	5.22	68,000	3.7-4.3	17	-	-
NaI:Tl	Strong	3.67	45,000	7.1	230	-	-

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FIGURE 11: The R&D works on new Cs-Cu-I based crystals by SIC group [43].

5. SUMMARY

For better detection and measurements of dark matter and neutrinos, low-threshold strategies and technologies are reviewed in this note. The low-threshold technology development of scintillation detectors is discussed in particular. A prototype of a dual-phase liquid argon detector and its results are discussed, which can already reach the typical performance in the literature. It shows the potential to reach a sub-KeV threshold for future CEνNS with reactor neutrino. The liquid scintillation detectors of JUNO and JUNO-TAO for neutrinos are also discussed aiming for neutrino measurements with a sub-MeV threshold. Some new technologies are discussed such as the water-based directional LS and a new type of crystals with higher light yield, which are also valuable directions for future application.

CONFLICTS OF INTEREST

The author declares that there are no conflicts of interest regarding the publication of this paper.

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