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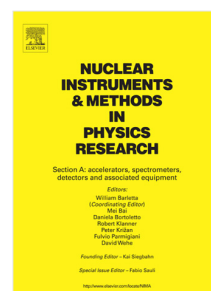
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# Journal Pre-proof

Optimization of the JUNO liquid scintillator composition using a Daya Bay antineutrino detector

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R. Leitner, J. Leung, C. Li, D.M. Li, F. Li, F. Li, H.T. Li, H.L. Li, J. Li, J.J. Li, J.Q. Li, K.J. Li, M.Z. Li, N. Li, N. Li, Q.J. Li, Q.J. Li, R.H. Li, S.C. Li, S.F. Li, S.J. Li, T. Li, T. Li, W.D. Li, W.G. Li, X.M. Li, X.N. Li, X.L. Li, X.Q. Li, Y. Li, Y.F. Li, Z.B. Li, Z.Y. Li, H. Liang, H. Liang, J.J. Liang, D. Liebau, A. Limphirat, S. Limpijumnong, C.J. Lin, G.L. Lin, S.X. Lin, T. Lin, Y.H. Lin, J.J. Ling, J.M. Link, I. Lippi, L. Littenberg, B.R. Littlejohn, F. Liu, H. Liu, H. Liu, H.B. Liu, H.D. Liu, H.J. Liu, H.T. Liu, J.C. Liu, J.L. Liu, M. Liu, Q. Liu, Q. Liu, R.X. Liu, S.Y. Liu, S.B. Liu, S.L. Liu, X.W. Liu, Y. Liu, A. Lokhov, P. Lombardi, K. Loo, S. Lorenz, C. Lu, C. Lu, H.Q. Lu, J.B. Lu, J.G. Lu, S.X. Lu, X.X. Lu, B. Lubsandorzhiev, S. Lubsandorzhiev, L. Ludhova, K.B. Luk, F.J. Luo, G. Luo, P.W. Luo, S. Luo, W.M. Luo, V. Lyashuk, Q.M. Ma, S. Ma, X.B. Ma, X.Y. Ma, Y.Q. Ma, Y. Malyshkin, F. Mantovani, Y.J. Mao, S.M. Mari, F. Marini, S. Marium, C. Marshall, C. Martellini, G. Martin-Chassard, D.A. Martinez Caicedo, A. Martini, J. Martino, D. Mayilyan, K.T. McDonald, R.D. McKeown, A. Müller, G. Meng, Y. Meng, A. Merzaglia, E. Meroni, D. Meyhöfer, M. Mezzetto, J. Miller, L. Miramonti, S. Monforte, P. Montini, M. Montuschi, N. Morozov, P. Muralidharan, J. Napolitano, M. Nastasi, D.V. Naumov, E. Naumova, I. Nemchenok, A. Nikolaev, F.P. Ning, Z. Ning, H. Nunokawa, L. Oberauer, J.P. Ochoa-Ricoux, A. Olshevskiy, F. Ortica, H.R. Pan, A. Paoloni, J. Park, N. Parkalian, S. Parmeggiano, S. Patton, T. Payupol, V. Pec, D. Pedretti, Y.T. Pei, N. Pelliccia, A.G. Peng, H.P. Peng, J.C. Peng, F. Perrot, P.A. Petitjean, L.F. Pineres Rico, A. Popov, P. Poussot, W. Pratumwan, E. Previtali, C.S.J. Pun, F.Z. Qi, M. Qi, S. Qian, X. Qian, X.H. Qian, H. Qiao, Z.H. Qin, S.K. Qiu, M. Rajput, G. Ranucci, N. Raper, A. Re, H. Rebber, A. Rebbi, B. Ren, J. Ren, C.M. Reveco, T. Rezinko, B. Ricci, M. Robens, M. Roche, N. Rodphai, L. Rohwer, A. Romani, R. Rosero, B. Roskovec, C. Roth, X.C. Ruan, X.D. Ruan, S. Rujirawat, A. Rybnikov, A. Sadovsky, P. Saggese, G. Salamanna, A. Sangka, N. Sanguansak, U. Sawangwit, J. Sawatzki, F. Sawy, M. Schever, J. Schuler, C. Schwab, K. Schweizer, D. Selivanov, A. Selyunin, A. Serafini, G. Settanta, M. Settimo, M. Shahzad, G. Shi, J.Y. Shi, Y.J. Shi, V. Shutov, A. Sidorenkov, F. Simkovic, C. Sirignano, J. Siripak, M. Sisti, M. Slupecki, M. Smirnov, O. Smirnov, T. Sogo-Bezerra, J. Songwadhana, B. Soonthornthum, A. Sotnikov, O. Sramek, W. Sreethawong, A. Stahl, L. Stanco, K. Stankevich, D. Stefanik, H. Steiger, H. Steiner, J. Steinmann, M. Stender, V. Strati, A. Studenikin, G.X. Sun, L.T. Sun, J.L. Sun, S.F. Sun, X.L. Sun, Y.J. Sun, Y.Z. Sun, N. Suwonjandee, M. Szelezniak, J. Tang, Q. Tang, Q. Tang, X. Tang, A. Tietzsch, I. Tkachev, T. Tmej, K. Treskov, G. Troni, W. Trzaska, W.-H. Tse, C.E. Tull, C. Tuve, S. van Waasen, J. Vanden Boom, N. Vassilopoulos, V. Vedin, G. Verde, M. Vialkov, B. Viaud, B. Viren, C. Volpe, V. Vorobel, L. Votano, P. Walker, C. Wang, C.H. Wang, E. Wang, G.L. Wang, J. Wang, J. Wang, K.Y. Wang, L. Wang, M.F. Wang, M. Wang, M. Wang, N.Y. Wang, R.G. Wang, S.G. Wang, W. Wang, W. Wang, W.S. Wang, X. Wang, X.Y. Wang, Y. Wang, Y. Wang, Y. Wang, Y.F. Wang, Y.G. Wang,

Y.M. Wang, Y.Q. Wang, Z. Wang, Z. Wang, Z.M. Wang, Z.Y. Wang, A. Watcharangkool, H.Y. Wei, L.H. Wei, W. Wei, Y.D. Wei, L.J. Wen, K. Whisnant, C.G. White, C. Wiebusch, S.C.F. Wong, H.L.H. Wong, B. Wonsak, E. Worcester, C.H. Wu, D.R. Wu, F.L. Wu, Q. Wu, W.J. Wu, Z. Wu, M. Wurm, J. Wurtz, C. Wysotzki, Y.F. Xi, D.M. Xia, Y.G. Xie, Z.Q. Xie, Z.Z. Xing, D.L. Xu, F.R. Xu, H.K. Xu, J.L. Xu, J. Xu, M.H. Xu, T. Xu, Y. Xu, Y. Xu, T. Xue, B.J. Yan, X.B. Yan, Y.P. Yan, A.B. Yang, C.G. Yang, H. Yang, J. Yang, L. Yang, X.Y. Yang, Y.F. Yang, Y.Z. Yang, H.F. Yao, Z. Yasin, J.X. Ye, M. Ye, U. Yegin, M. Yeh, F. Yermia, P.H. Yi, Z.Y. You, B.L. Young, B.X. Yu, C.X. Yu, C.Y. Yu, H.Z. Yu, M. Yu, X.H. Yu, Z.Y. Yu, C.Z. Yuan, Y. Yuan, Z.X. Yuan, Z.Y. Yuan, B.B. Yue, N. Zafar, A. Zambanini, P. Zeng, S. Zeng, T.X. Zeng, Y.D. Zeng, L. Zhan, C. Zhang, F.Y. Zhang, G.Q. Zhang, H.H. Zhang, H.Q. Zhang, J. Zhang, J.B. Zhang, J.W. Zhang, P. Zhang, Q.M. Zhang, T. Zhang, X.M. Zhang, X.T. Zhang, Y. Zhang, Y.H. Zhang, Y.M. Zhang, Y.P. Zhang, Y.X. Zhang, Y.Y. Zhang, Y.Y. Zhang, Z.J. Zhang, Z.P. Zhang, Z.Y. Zhang, Z.Y. Zhang, F.Y. Zhao, J. Zhao, R. Zhao, S.J. Zhao, T.C. Zhao, D.Q. Zheng, H. Zheng, M.S. Zheng, Y.H. Zheng, W.R. Zhong, J. Zhou, L. Zhou, N. Zhou, S. Zhou, X. Zhou, J. Zhu, K.J. Zhu, H.L. Zhuang, L. Zong, J.H. Zou

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## Optimization of the JUNO liquid scintillator composition using a Daya Bay antineutrino detector

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### Abstract

To maximize the light yield of the liquid scintillator (LS) for the Jiangmen Underground Neutrino Observatory (JUNO), a 20 t LS sample was produced in a pilot plant at Daya Bay. The optical properties of the new LS in various compositions were studied by replacing the gadolinium-loaded LS in one antineutrino detector. The concentrations of the fluor, PPO, and the wavelength shifter, bis-MSB, were increased in 12 steps from 0.5 g/L and <0.01 mg/L to 4 g/L and 13 mg/L, respectively. The numbers of total detected photoelectrons suggest that, with the optically purified solvent, the bis-MSB concentration does not need to be more than 4 mg/L. To bridge the one order of magnitude in the detector size difference between Daya Bay and JUNO, the Daya Bay data were used to tune the parameters of a newly developed optical model. Then, the model and tuned parameters were used in the JUNO simulation. This enabled to determine the optimal composition for the JUNO LS: purified solvent LAB with 2.5 g/L PPO, and 1 to 4 mg/L bis-MSB.

*Keywords:* neutrino, liquid scintillator, light yield

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## 1. Introduction

Liquid scintillator (LS) detectors readout by photomultiplier tubes (PMTs) have supported neutrino physics for several decades, from the discovery of neutrinos in the 1950s [1], to the precise measurement of the neutrino mass squared splitting  $\Delta m_{21}^2$  at KamLAND [2], the precise measurement of solar neutrinos at Borexino [3], and the observation of the  $\theta_{13}$ -driven neutrino oscillation at Daya Bay [4]. Given the high light yield, good transparency and relatively low price, this kind of detector is also adopted by the Jiangmen Underground Neutrino Observatory (JUNO) [5, 6], which utilizes 20 kt LS with one of the physics goals of determining the neutrino mass ordering. Since the sensitivity comes from a precise measurement of the fine structure in the oscillated neutrino spectrum, a crucial requirement on the JUNO detector is the excellent energy resolution,  $\sim 3\%$  at 1 MeV, corresponding to at least 1100 detected photoelectrons (p.e.) per MeV of deposited energy [5]. The number of detected p.e. per MeV is referred to as ObsLY hereafter. The higher ObsLY is, the better the energy resolution and the physics sensitivity are. Thus, one of the keys of the JUNO detector development is to maximize ObsLY.

In recent LS experiments, a widely used solvent is linear alkylbenzene (LAB), with 2,5-diphenyloxazole (PPO) as the fluor and p-bis-(o-methylstyryl)-benzene (bis-MSB) as the wavelength shifter. The ionization of a charged particle excites the LAB molecules. A fraction of the excitation energy is transferred to the PPO. Scintillation photons are generated from the de-excitation of PPO molecules. The total number of photons released by PPO is defined as the initial light yield, which rapidly increases with the PPO concentration before reaching 2 g/L. Above this concentration the increase becomes much less steep. The wavelengths of most initial photons are shifted to longer wavelengths by the absorption and re-emission of bis-MSB. This shift is crucial as the long wavelength avoids spectral self-absorption by the solvent and allows the photons to reach PMTs far away from the energy deposit points. Eventually, ObsLY is a joint effect of the initial light yield, the photon absorption and re-emission during propagation, and the wavelength-dependent PMT quantum efficiency (QE). To obtain the maximum ObsLY, these aspects must be simultaneously optimized.

There have been many studies that independently measured the optical properties of LS, such as Refs. [7, 8, 9] for the initial light yields, Refs. [10, 11, 12] for the transparency. To completely deal with the competing photon absorption and subsequent re-emission processes of the LS components, a comprehensive optical model was developed and reported in Ref. [13]. However, the parameters used in the model were obtained from bench-top experiments with a typical detector size of a few centimeters. Before usage in JUNO, a spherical LS detector with an inner diameter of 35.4 m, the model and its parameters should be validated based on data collected in a larger detector.

This requirement motivated a dedicated LS experiment at Daya Bay. A LS pilot plant was built by the JUNO collaboration in the underground LS hall of Daya Bay. One Daya Bay antineutrino detector (AD) [14, 15] in the Experimental Hall 1 (EH1-AD1) stopped data taking in January 2017. The 20 t gadolinium-loaded LS (Gd-LS) in the innermost cylindrical vessel with 3 m in diameter and height was replaced with purified LS produced by the pilot plant. PPO and bis-MSB concentrations were 0.5 g/L and less than 0.01 mg/L, and then increased in 12 steps to 4 g/L and 13 mg/L, respectively. The ObsLY in the 13 samples was measured at 0.5% precision level. The above-mentioned optical model was successfully tuned to the data. This allowed to identify the optimal scintillator composition for the final JUNO detector.

The structure of this paper is as follows: Sec. 2 describes the Daya Bay AD and the LS replacement experiment. Section 3 presents results of the ObsLY measurements. Section 4 discusses the determination of the JUNO LS composition using the optical model tuned to Daya Bay data.

## 2. The JUNO LS pilot experiment at Daya Bay

The Daya Bay reactor neutrino experiment started data taking on December 24, 2011. With millions of  $\bar{\nu}_e$  interactions detected in eight identically designed ADs in three underground EHs, many physics results have been produced, including the current world-leading measurements of the neutrino mixing angle  $\theta_{13}$  and the squared mass-splitting  $|\Delta m_{32}^2|$  [16], precise measurements of the reactor  $\bar{\nu}_e$  flux and spectrum [17, 18, 19], and stringent limits on the existence of light sterile neutrinos [20, 21]. Three nested cylindrical volumes in each AD are separated by concentric acrylic vessels (IAV, OAV), as shown in Fig. 1. The innermost volume is filled with 20 t of Gd-LS, serving as the primary  $\bar{\nu}_e$  target. It is surrounded by  $\sim 22$  t of non-loaded LS to detect  $\gamma$ -rays escaping from the target volume. The outermost volume is filled with mineral oil to shield the LS from natural radioactivity. A total of 192 8-inch PMTs (Hamamatsu R-5912) are installed on the steel vessel to detect scintillation photons. There are three Automated Calibration Units (ACUs) on the top of each AD to calibrate the energy response along the vertical axes at the detector

52 center (ACU-A), the edge of the Gd-LS volume (ACU-B, removed for the replacement experiment), and the LS  
 53 volume (ACU-C). Details of the detector systems are reported in Refs. [14, 15, 22].

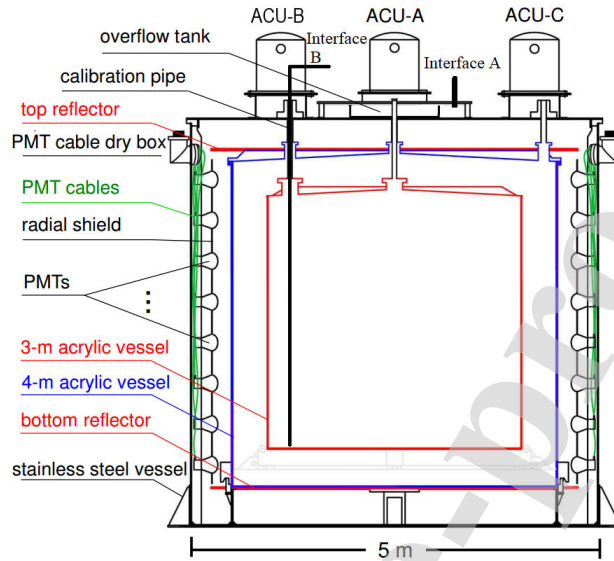


Figure 1: Schematic of a Daya Bay antineutrino detector. The three cylindrical volumes, defined by two acrylic vessels, are filled with Gd-LS, LS, and mineral oil from the innermost to the outermost. Three Automated Calibration Units are installed on top of the detector to calibrate the detector's energy response. Two interfaces are installed on the top of EH1-AD1 for the LS replacement experiment, one through the central overflow tank and the other one using the port of ACU-B.

54 Figure 2 shows photographs of the LS experiment, including the pilot plant, the LS replacement system and  
 55 EH1-AD1. The pilot plant built in the LS hall consisted of four primary subsystems for purification in sequence: the  
 56  $\text{Al}_2\text{O}_3$  column, the distillation, the water extraction and the steam stripping. In addition there were several supporting  
 57 subsystems for the PPO and bis-MSB dissolution, and the generation of purified water and nitrogen. To control the  
 58 optical qualities, an apparatus with a 1-m long tube was built to measure the light attenuation in the liquids. The  
 59 20 t LAB produced by the Jinling LAB factory was purified by the  $\text{Al}_2\text{O}_3$  column for optical transparency and then  
 60 distilled for radiopurity. About 11.6 kg PPO produced by the Haiso Technology Co., LTD was dissolved and added  
 61 to the LAB. Thus, the initial LS composition was 0.5 g/L PPO without bis-MSB. Before filling AD1, the mixture went  
 62 through the water extraction and steam stripping systems for radiopurity. Details of the distillation and steam stripping  
 63 systems have been reported in Ref. [23]. The attenuation length of the purified LAB was measured to be 25.1 m at  
 64 the photon wavelength of 430 nm, and the attenuation length of the initial LS was 23.8 m. The uncertainties of these  
 65 values were about 2 m, primarily from the relatively short light path compared to the attenuation length.

66 A replacement system was set up in EH1 to drain the Gd-LS and refill the IAV with new LS. The system consisted  
 67 of three pumps, three buffer tanks and stainless steel pipes connecting to the two interfaces on AD1. The central  
 68 interface A for injecting liquids was installed via the central overflow tank while the draining was performed via an  
 69 acrylic tube inserted to the bottom of IAV through the interface B. The ACU-B was removed for installing the interface  
 70 B. In fact, the liquids could be filled or drained from either interfaces. The system could run in a self-circulation or  
 71 a full-circulation mode. In the former mode, liquids were pumped from the IAV to a 300 L buffer tank and then  
 72 re-inserted into the IAV. In the latter mode, liquids in the IAV were drained and sent to the facilities in the LS hall for  
 73 further processing, while newly produced liquids or the re-processed ones were returned to the IAV.

74 To avoid mixing of the old Gd-LS and the new LS, the Gd-LS was replaced first by purified water that was then  
 75 replaced by the new LS. This replacement method was also required to prevent destructive stress on the acrylic vessels.  
 76 From February 16 to February 22 2017, the Gd-LS was drained at a rate of about 300 L/h through the central interface  
 77 while purified water was filled through the side interface. Then, the new LS with 0.5 g/L PPO was filled through the  
 78 central interface while water was drained through the side one. Limited by the position of the central interface A,  
 79 about 10 L Gd-LS could not be drained out. This resulted in a residual bis-MSB concentration of less than 0.01 mg/L,  
 80 confirmed by the light absorption measurement with a UV-vis spectrometer. In addition, since the tube through the  
 81 interface B could not touch the IAV bottom, a layer of water with a thickness of about 1 cm was left. Eventually, the



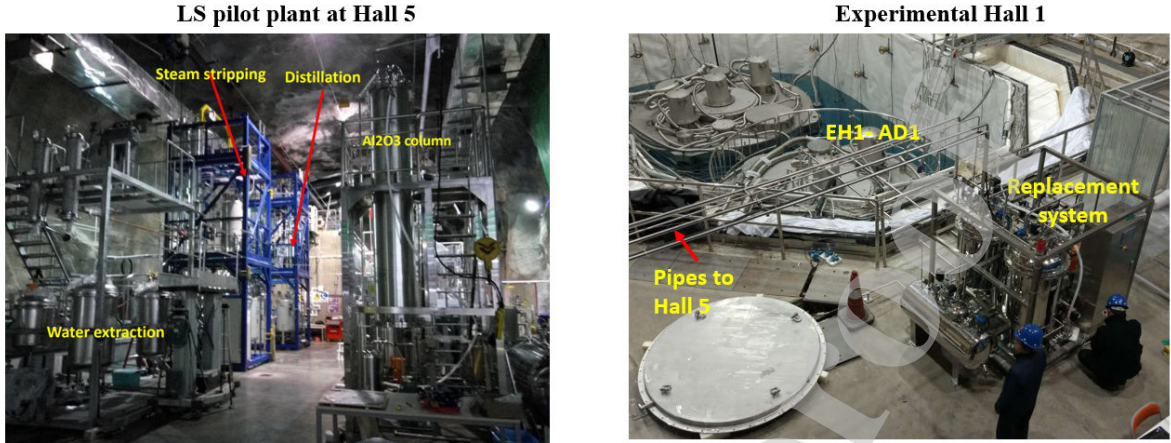


Figure 2: Photographs of EH1-AD1, the replacement system in EH1, and the pilot plant in the LS hall (Hall 5).

Step	PPO	bis-MSB	Date of calibration	LS temperature	ObsLY (p.e./MeV)
Initial	0.5 g/L	<0.01 mg/L	April 28, 2017	22.6 °C	123.7
1	1.0 g/L	<0.01 mg/L	May 28, 2017	22.6 °C	150.3
2	2.0 g/L	<0.01 mg/L	June 4, 2017	22.5 °C	167.7
3	2.0 g/L	0.1 mg/L	June 9, 2017	22.6 °C	177.2
4	2.0 g/L	1.0 mg/L	June 13, 2017	22.6 °C	183.2
5	2.0 g/L	4.0 mg/L	June 18, 2017	22.6 °C	184.3
6	2.0 g/L	7.0 mg/L	June 23, 2017	22.6 °C	184.8
7	2.5 g/L	7.0 mg/L	June 29, 2017	22.6 °C	189.5
8	3.0 g/L	7.0 mg/L	July 5, 2017	22.6 °C	191.6
9	3.5 g/L	7.0 mg/L	July 11, 2017	22.6 °C	192.6
10	4.0 g/L	7.0 mg/L	July 17, 2017	22.7 °C	192.6
11	4.0 g/L	10.0 mg/L	July 22, 2017	22.7 °C	193.0
12	4.0 g/L	13.0 mg/L	July 27, 2017	22.7 °C	193.3

Table 1: Summary of the LS experiment. Each LS composition change took 4 to 5 days, including a slow addition of PPO or bis-MSB over 1.5 days followed by at least 3 days of self-circulation. The ObsLY was measured to a precision of 0.5% using a  $^{60}\text{Co}$  calibration source in the detector center.

82 replacement was successfully finished on March 7. To obtain the radiopurity of LS with 0.5 g/L PPO, the replacement  
 83 system was shut down after ten days of self-circulation. The LS radiopurity was measured later in May to wait for the  
 84 decay of the  $^{222}\text{Rn}$  contamination.

85 Beginning on May 20, PPO and bis-MSB were added in 12 steps as summarized in Table 1. In each step, the  
 86 replacement system was working in the full-circulation mode. The LS was pumped out with a 300 L/h speed and sent  
 87 to a buffer tank of the water extraction system in the LS hall. The PPO or bis-MSB was dissolved and slowly added to  
 88 the buffer tank in 36 hours. During this time about half of the total LS volume was circulated. Then, the replacement  
 89 system ran in the self-circulation mode with a 300 L/h rate for about three days to obtain the uniform fluor distribution  
 90 in the IAV. The fluor concentration was measured every 12 hours with a UV-vis spectrometer. In general, after two  
 91 days of self-circulation the concentration was stabilized at the target value. In the following the detector response was  
 92 calibrated by deploying  $^{60}\text{Co}$  calibration sources along ACU-A and ACU-C. The procedure generally took about six  
 93 hours. ObsLY was determined using the data collected with the  $^{60}\text{Co}$  source deployed in the detector center.

### 94 3. The light yield measurements

95 The scintillation photons are detected by the 192 PMTs of the AD, operating at an average gain of  $1 \times 10^7$ . All the  
 96 PMTs were working without problems over the three-months period. In the Daya Bay readout system, after an initial



97 fast amplification, the PMT signal is fed to a pulse shaping circuit consisting of a differential CR and four integrating  
 98 RC circuits (CR-(RC)<sup>4</sup>), and then amplified by a factor of ten. The integrated value, sampled by a 40-MHz 12-bit  
 99 ADC, is used as an estimate of the PMT charge output [24]. The PMT gains were separately calibrated in the thirteen  
 100 measurements, using the PMT dark noises captured by the data acquisition system. The CR-(RC)<sup>4</sup> shaping circuit,  
 101 combined with the time distribution of detected light, introduces a ~10% nonlinearity in the charge measurement  
 102 of a single channel, dubbed the electronics nonlinearity. From the initial concentration to the 6<sup>th</sup> step in Table 1,  
 103 this electronics nonlinearity was carefully measured and corrected with the help of a full Flash ADC readout system  
 104 following the method reported in Ref. [25]. From the 7<sup>th</sup> to 12<sup>th</sup> steps, the Flash ADC readout system was not working  
 105 well. Therefore, the measured nonlinearity in the 6<sup>th</sup> step was used to correct nonlinearities in the 7<sup>th</sup> to 12<sup>th</sup> steps.  
 106 Such corrections were feasible because the time distributions of detected light were found to be stable in the 6<sup>th</sup> to 12<sup>th</sup>  
 107 steps.

108 For each concentration, ObsLY was determined by measuring the scintillation light originating from the two  
 109  $\gamma$ -rays of <sup>60</sup>Co decays, corresponding to a total deposit energy of 2.505 MeV. Figure 3 and Table 1 summarize the  
 110 measured light yields with the 13 LS compositions. For the first three steps with less than 0.01 mg/L bis-MSB from  
 111 residual Gd-LS, the light yield increased by more than 40% with PPO concentrations increasing from 0.5 g/L to 2 g/L.  
 112 Adding 1 mg/L bis-MSB further increased the light yield by 10%. However, no significant increase was found when  
 113 further raising the bis-MSB concentration. This indicates that for the very transparent LAB, scintillation light emitted  
 114 by PPO would either be absorbed and re-emitted by bis-MSB, or directly reach the PMTs. Adding more bis-MSB  
 115 does only shift the fractions of photons from PPO and bis-MSB when reaching the PMTs. In addition, after adding  
 116 bis-MSB, the increase of PPO to more than 2.5 g/L yielded no obvious effect on ObsLY, suggesting the initial light  
 117 yield had reached the plateau for particles with low energy deposit density, such as  $\gamma$ 's and  $e^{\pm}$ 's.

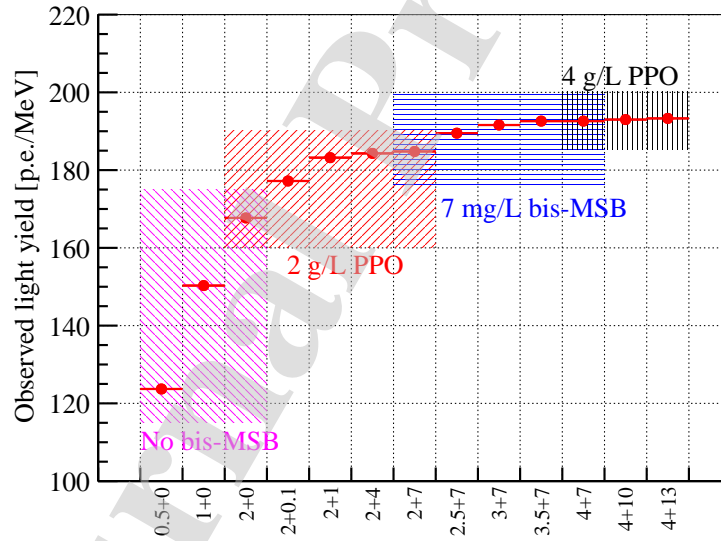


Figure 3: Measured light yields ObsLY versus PPO and bis-MSB concentrations. The labels of the horizontal axis are the concentrations of PPO (g/L) plus that of bis-MSB (mg/L). The vertical error bar (0.2%) is statistical only and too small to be visible. The points in each colored box are measured at the same PPO or bis-MSB concentration.

118 To compare ObsLY of different LS compositions, we have considered the relative uncertainties mainly arising  
 119 from three sources: the LS temperature variation, the statistical fluctuations in the determination of PMT gains and of  
 120 the <sup>60</sup>Co peak, and the electronics nonlinearity correction. The LS temperature was monitored using four sensors and  
 121 was found to be stable within 0.2 °C over the three months, resulting in a less than 0.1% light yield variation based  
 122 on the measurements in Ref. [26]. The second term is estimated to be at 0.2% level according to the fitted energy  
 123 peak position of the <sup>60</sup>Co source. The third term is less than 0.5% for each measurement as discussed in Ref. [25].  
 124 Combining the three sources, the uncertainty of each light yield measurement is estimated to be 0.5%.

125 From August 2017 to January 2019, several rounds of radiopurity studies have been carried out. In this period,  
 126 the LS composition was kept at 4 g/L PPO and 13 mg/L bis-MSB. A stable ObsLY was found within  $\pm 0.5\%$  as shown  
 127 in Fig. 4.

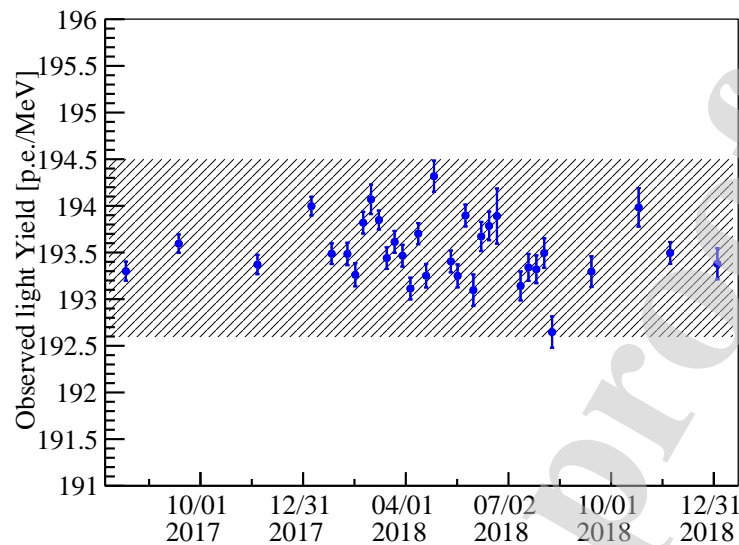


Figure 4: ObsLY of the new LS with 4 g/L PPO and 13 mg/L bis-MSB kept stable within  $\pm 0.5\%$  (the shaded band) between August 2017 and January 2019. The uncertainties are dominated by statistics of the  $^{60}\text{Co}$  calibration events.

#### 4. Optimization of the JUNO LS composition

The ObsLY measurements performed at Daya Bay are of great importance to future LS experiments, such as JUNO, for the determination of the LS composition. However, ObsLY of Daya Bay cannot be directly used in JUNO, since ObsLY is affected by a few factors, such as the initial light yield, the self-absorption and re-emission effects during propagation, and the PMT QE spectra. The 20 kt LS of JUNO are contained in a spherical acrylic vessel with an inner diameter of 35.4 m. Scintillation light is detected by about 18,000 20-inch PMTs, including 5,000 Hamamatsu R-12860 dynode PMTs, and 13,000 NNVT GDG-6201 PMTs with a microchannel plate (MCP-PMT) instead of a dynode structure. In Daya Bay the new LS was studied in a cylindrical vessel with 3 m in height and diameter, and Hamamatsu R-5912 8-inch PMTs were used.

To take these differences into account, a newly developed optical model [13] has been implemented in the simulation of both experiments. The model is designed to thoroughly deal with the competing photon absorption and subsequent re-emission processes of the LS components. It starts with primary scintillation photons emitted by PPO. During the propagation, a photon could either be absorbed, or be scattered, or vanish when reaching optical boundaries such as PMTs. The absorption could happen on any LS component, according to the Beer-Lambert law and the absorption spectrum of each component. A new photon with longer wavelength may be emitted if the original photon is absorbed by PPO or bis-MSB. The re-emission probability is defined as the fluorescence quantum efficiency. In this model, scattering of optical photons happens via the Rayleigh process. Once a photon is scattered, it changes direction and continues propagation. The Rayleigh scattering length of LAB is found to be  $27.0 \pm 2.3$  m at 430 nm [27]. Thus, key optical parameters in the model consist of emission spectra of PPO and bis-MSB, absorption spectra of LAB, PPO and bis-MSB, and wavelength-dependent fluorescence quantum efficiencies of PPO and bis-MSB.

The measurements of the key optical parameters are described below and in Ref. [13]. The emission spectra of PPO and bis-MSB were well measured with a Fluorolog Tau-3 spectrometer as shown in Fig. 5. The absorption spectrum of each LS component used in Daya Bay and the pilot plant was measured using a Shimadzu UV2550 UV-vis spectrometer and quartz cuvettes with different light paths up to 10 cm. To overcome the large uncertainty due to limited cuvette sizes and the long absorption length at photon wavelength of 430 nm, a 1-m long tube was used to measure the attenuation length. Then, the absorption length were obtained by subtracting the Rayleigh scattering length from the attenuation one. Comparison of absorption spectra among the Daya Bay original liquids and the purified JUNO liquids is shown in Fig. 6. The purification significantly improved the transparencies of LAB and PPO. The general method to measure fluorescence QE was using the combination of a fluorescence spectrometer and a UV-Vis spectrometer. An average QE spectrum from several measurements [10, 11, 12] was adopted in the simulation, shown as the default QE spectra in Fig. 5. Due to intrinsic difficulties of several corrections in this method,

159 the measured efficiencies had relatively large uncertainties, typically 5%.

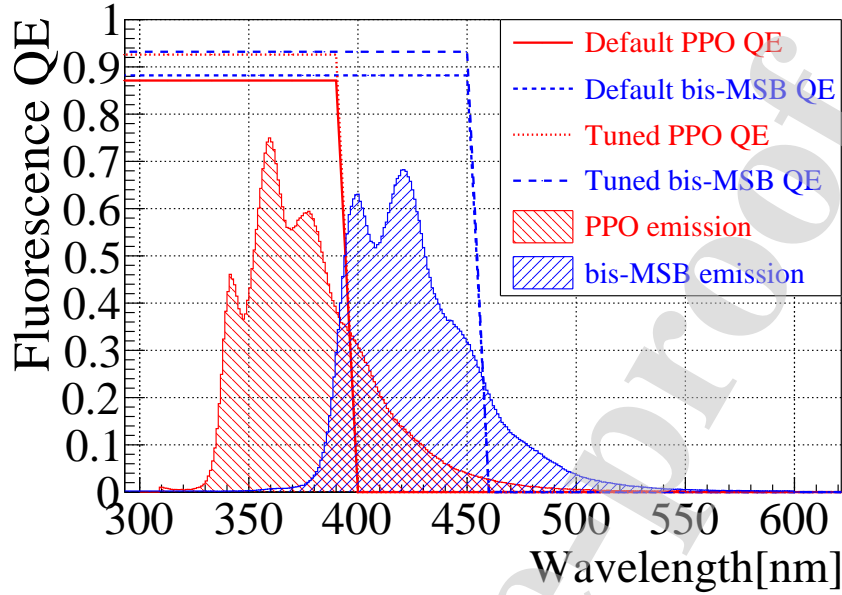


Figure 5: Emission spectra of PPO and bis-MSB in arbitrary units, and their QE efficiencies. The default PPO QE spectra are from the average of three bench-top measurements, while the tuned ones are from the tuning based on Daya Bay data taken in LS experiment in Table 1.

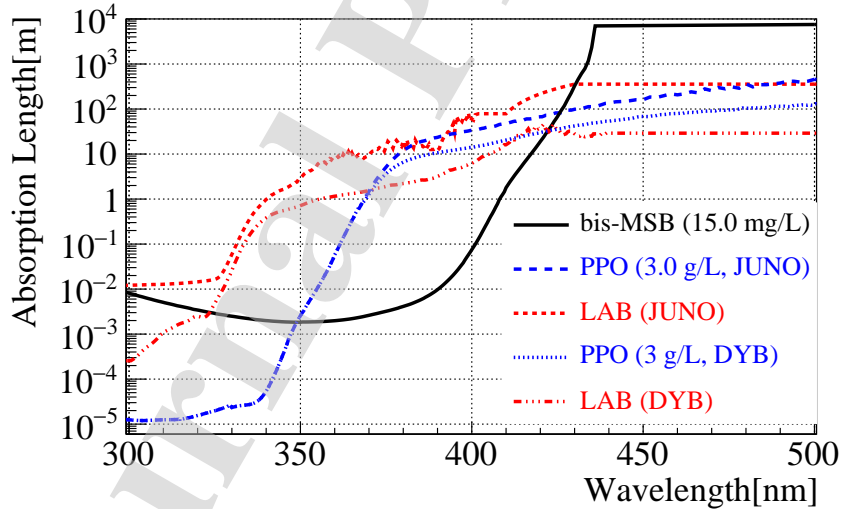


Figure 6: Comparison of the absorption spectra of LAB and PPO used in Daya Bay and produced by JUNO pilot plant. The purification significantly improved the optical transparency.

160 The optical model has been implemented in the Geant4 [28] based Daya Bay simulation. The residual 1-cm  
 161 water at the bottom of IAV has been included in the simulation by assuming a perfect surface between the water and  
 162 the LS. The bis-MSB of less than 0.01 mg/L from the residual Gd-LS is also included. The simulated light yields  
 163 with respect to bis-MSB concentrations are compared with the experimental data, as shown in Fig. 7. If the absorption  
 164 spectra of Daya Bay liquids are used, a much steeper ObsLY increase is found, because LAB, which does not re-emit  
 165 a new photon after the absorption, strongly competes with bis-MSB in the wavelength range of 350 to 400 nm. More  
 166 bis-MSB leads to more photons shifting to the wavelength range above 420 nm, in which the liquids are much more  
 167 transparent. Thus, the ObsLY monotonically increases with the bis-MSB concentration. Once the absorption spectra  
 168 of JUNO liquids are employed, the importance of bis-MSB is significantly reduced, and most of the photons emitted

169 by PPO could reach the Daya Bay LS contained in the outer acrylic vessel before absorption by LAB. However, at  
 170 bis-MSB concentrations of smaller than 1 mg/L, the bis-MSB plays a less important role in the data compared to the  
 171 simulation. Varying the absorption spectra of each component at wavelengths longer than 420 nm does not reduce  
 172 the discrepancy. Changing the height of the bis-MSB QE spectrum, and shifting the cutoff position of the PPO and  
 173 bis-MSB QE spectra have minor impacts on the discrepancy. Eventually, the PPO fluorescence QE is increased by  
 174 5% as shown in Fig. 5. Once a photon is absorbed by PPO, the probability of re-emitting a new photon with longer  
 175 wavelength is closer to 1. In this way, the discrepancy between simulation and data is improved from about 2% to  
 176 better than 1%.

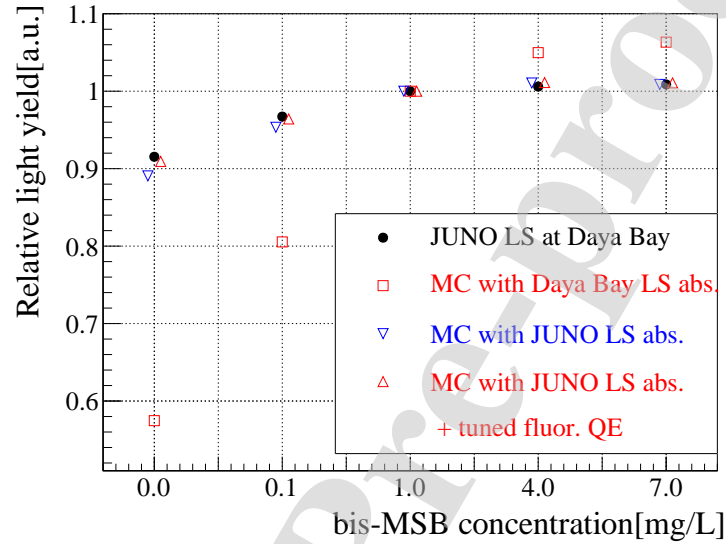


Figure 7: Comparison of the measured and simulated light yields with 2 g/L PPO and various bis-MSB concentrations. Each group is normalized at 1 mg/L bis-MSB. The JUNO LS data in the Daya Bay detector are drawn as the black dots. If the optical properties of Daya Bay LS are used in the simulation, large discrepancies are found as the black squares. Using the default optical properties of JUNO LS in Fig. 5 and Fig. 6, the simulation results (blue inverted triangles) have a much better agreement with data. After increasing the PPO fluorescence quantum efficiencies, the agreement is improved from 2% to 1% (red triangles) at low bis-MSB concentrations. For better visibility, the triangles and inverted triangles are slightly shifted to the right and the left, respectively.

177 The first application of the tuned model is to extract the initial light yields with different PPO concentrations.  
 178 As mentioned before, ObsLY is a joint effect of the initial light yield, the absorption and re-emission, and the  
 179 PMT response. A set of simulation is performed for the Daya Bay AD with LS compositions with different PPO  
 180 concentrations and 7 mg/L bis-MSB. The same initial light yield is used in the simulation to solely study the self-  
 181 absorption effect of PPO. The simulation results are listed in Table 2. Each 0.5 g/L PPO increase leads to about  
 182 0.5% loss of ObsLY in the simulation. Thus, the initial light yields are obtained by dividing the Daya Bay measured  
 183 ObsLY with the simulated ones, and will be used in the determination of the JUNO LS composition.

PPO concentration	ObsLY		Initial light yield
	Measured	Simulated	
2.0 g/L	1	1	1
2.5 g/L	1.025	0.994	1.031
3.0 g/L	1.037	0.991	1.046
3.5 g/L	1.042	0.986	1.057
4.0 g/L	1.042	0.982	1.061

Table 2: Relative ObsLY with respect to PPO concentrations in the data and the simulation, normalized at 2 g/L PPO. In the simulation the initial light yield is fixed to solely study the PPO self-absorption effects. The initial light yields are extracted by dividing the measured values with the simulated ones.

184 The optical model, the measured absorption spectra, the tuned fluorescence quantum efficiencies, and the  
 185 extracted initial light yields have been employed in the JUNO simulation. The simulated ObsLY with respect to PPO

186 and bis-MSB concentrations is shown in Fig. 8. The normalization point is chosen as 2.5 g/L PPO and 2 mg/L bis-  
 187 MSB, at which the largest light yield is found. Although the ObsLY monotonically increases with PPO concentrations  
 188 at Daya Bay, 2.5 g/L PPO is preferred at JUNO due to the non-negligible self-absorption in the larger detector. The  
 189 optimal bis-MSB concentration could be in the range of 1 mg/L to 4 mg/L, since the ObsLY difference is less than 1%  
 190 in this range. Combining the absorption of each component, and the scattering of LAB, the LS attenuation length with  
 191 this composition is about 20.4 m at 430 nm. It fulfills the requirement in the JUNO Conceptual Design Report [5].

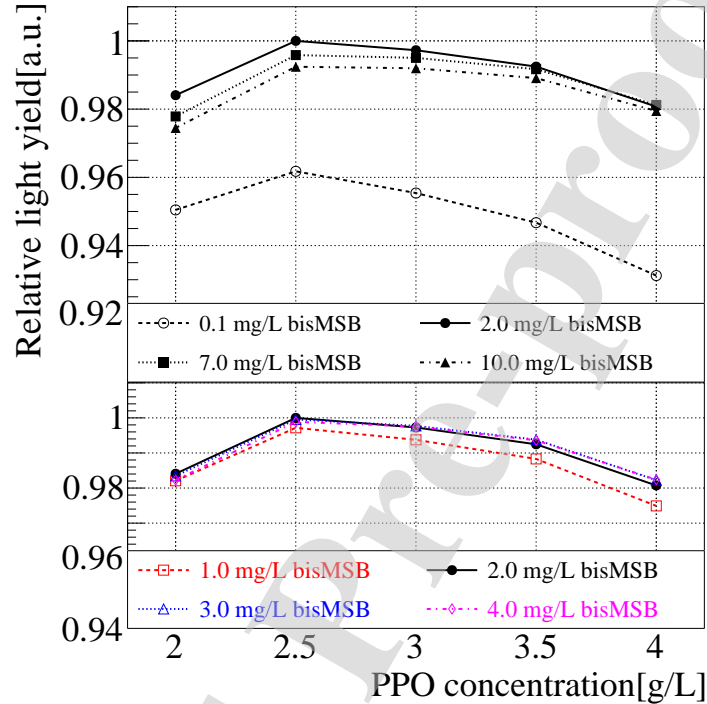


Figure 8: The simulated ObsLY with respect to PPO and bis-MSB concentrations in the JUNO detector. The tuned optical parameters, and the initial light yields in Table 2 are used in the simulation. For better visibility, the bis-MSB concentrations are divided to two groups which are shown in the top and bottom panel, respectively.

## 5. Summary

192 A precise measurement of ObsLY in various LS compositions has been performed in a Daya Bay AD, by replacing  
 193 the Gd-LS with purified LS produced in a pilot plant in the underground LS hall. For  $\gamma$ 's and  $e^\pm$ 's, ObsLY reaches a  
 194 plateau for PPO concentrations larger than 2.5 g/L. In addition, if the solvent is optically purified, the ObsLY increase  
 195 with respect to bis-MSB concentrations is negligible for concentrations larger than 4 mg/L. A novel optical model has  
 196 been employed to describe the complicated optical process in the liquids. The predicted ObsLY in different bis-MSB  
 197 concentrations agrees with these measurements within 1%. The initial light yields in various PPO concentrations  
 198 are extracted by subtracting the PPO self-absorption effect predicted by the optical model. To find the optimal LS  
 199 composition of JUNO, the model and the tuned optical parameters are used in the JUNO simulation. The results  
 200 suggest that in the JUNO-scale detector, either a PPO concentration larger than 2.5 g/L, or a bis-MSB concentration  
 201 bigger than 4 mg/L, would reduce the ObsLY. The JUNO LS composition is optimized to be the purified LAB with  
 202 2.5 g/L PPO and (1-4) mg/L bis-MSB. The optimization method can also be used in other future LS experiments.  
 203

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- 228 [1] C. L. Cowan, F. Reines, F. B. Harrison, H. W. Kruse, A. D. McGuire, Detection of the free neutrino: A Confirmation, *Science* 124 (1956)  
 229 103–104. doi:10.1126/science.124.3212.103.
- 230 [2] S. Abe, et al., Precision Measurement of Neutrino Oscillation Parameters with KamLAND, *Phys. Rev. Lett.* 100 (2008) 221803. arXiv:  
 231 0801.4589, doi:10.1103/PhysRevLett.100.221803.
- 232 [3] C. Arpesella, et al., Direct Measurement of the Be-7 Solar Neutrino Flux with 192 Days of Borexino Data, *Phys. Rev. Lett.* 101 (2008) 091302.  
 233 arXiv:0805.3843, doi:10.1103/PhysRevLett.101.091302.
- 234 [4] F. P. An, et al., Observation of electron-antineutrino disappearance at Daya Bay, *Phys. Rev. Lett.* 108 (2012) 171803. arXiv:1203.1669,  
 235 doi:10.1103/PhysRevLett.108.171803.
- 236 [5] Z. Djuricic, et al., JUNO Conceptual Design Report arXiv:1508.07166.
- 237 [6] F. An, et al., Neutrino Physics with JUNO, *J. Phys. G* 43 (3) (2016) 030401. arXiv:1507.05613, doi:10.1088/0954-3899/43/3/  
 238 030401.
- 239 [7] P. Lombardi, F. Ortica, G. Ranucci, A. Romani, Decay time and pulse shape discrimination of liquid scintillators based on novel solvents,  
 240 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 701  
 241 (2013) 133 – 144. doi:https://doi.org/10.1016/j.nima.2012.10.061.  
 242 URL <http://www.sciencedirect.com/science/article/pii/S0168900212012077>
- 243 [8] X.-C. Ye, et al., Preliminary study of light yield dependence on LAB liquid scintillator composition, *Chin. Phys. C* 39 (9) (2015) 096003.  
 244 arXiv:1506.00237, doi:10.1088/1674-1137/39/9/096003.
- 245 [9] J. Cumming, S. Hans, M. Yeh, Improving Light Yield Measurements for Low-Yield Scintillators, *Nucl. Instrum. Meth. A* 925 (2019) 1–5.  
 246 arXiv:1810.02885, doi:10.1016/j.nima.2019.01.014.
- 247 [10] X.-B. Li, H.-L. Xiao, J. Cao, J. Li, X.-C. Ruan, Y.-K. Heng, Timing properties and pulse shape discrimination of LAB-based liquid scintillator,  
 248 *Chinese Physics C* 35 (11) (2011) 1026–1032. doi:10.1088/1674-1137/35/11/009.  
 249 URL <https://doi.org/10.1088/1674-1137/35/11/009>
- 250 [11] X.-F. Ding, L.-J. Wen, X. Zhou, Y.-Y. Ding, X.-C. Ye, L. Zhou, M.-C. Liu, H. Cai, J. Cao, Measurement of the fluorescence quantum yield of  
 251 bis-MSB, *Chin. Phys. C* 39 (12) (2015) 126001. arXiv:1506.00240, doi:10.1088/1674-1137/39/12/126001.
- 252 [12] C. Buck, B. Gramlich, S. Wagner, Light propagation and fluorescence quantum yields in liquid scintillators, *JINST* 10 (09) (2015) P09007.  
 253 arXiv:1509.02327, doi:10.1088/1748-0221/10/09/P09007.
- 254 [13] Y. Zhang, Z. Yu, X. Li, Z. Deng, L. Wen, A complete optical model for liquid-scintillator detectors, *Nuclear Instruments and Methods in*  
 255 *Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 967 (2020) 163860. doi:https://doi.  
 256 org/10.1016/j.nima.2020.163860.  
 257 URL <http://www.sciencedirect.com/science/article/pii/S0168900220303648>
- 258 [14] F. P. An, et al., The Detector System of The Daya Bay Reactor Neutrino Experiment, *Nucl. Instrum. Meth. A* 811 (2016) 133–161. arXiv:  
 259 1508.03943, doi:10.1016/j.nima.2015.11.144.
- 260 [15] H. Band, et al., Assembly and Installation of the Daya Bay Antineutrino Detectors, *JINST* 8 (2013) T11006. arXiv:1309.1557, doi:  
 261 10.1088/1748-0221/8/11/T11006.
- 262 [16] D. Adey, et al., Measurement of the Electron Antineutrino Oscillation with 1958 Days of Operation at Daya Bay, *Phys. Rev. Lett.* 121 (24)  
 263 (2018) 241805. arXiv:1809.02261, doi:10.1103/PhysRevLett.121.241805.
- 264 [17] F. P. An, et al., Improved Measurement of the Reactor Antineutrino Flux and Spectrum at Daya Bay, *Chin. Phys. C* 41 (1) (2017) 013002.  
 265 arXiv:1607.05378, doi:10.1088/1674-1137/41/1/013002.
- 266 [18] F. P. An, et al., Evolution of the Reactor Antineutrino Flux and Spectrum at Daya Bay, *Phys. Rev. Lett.* 118 (25) (2017) 251801. arXiv:  
 267 1704.01082, doi:10.1103/PhysRevLett.118.251801.
- 268 [19] D. Adey, et al., Extraction of the  $^{235}\text{U}$  and  $^{239}\text{Pu}$  Antineutrino Spectra at Daya Bay, *Phys. Rev. Lett.* 123 (11) (2019) 111801. arXiv:

- 1904.07812, doi:10.1103/PhysRevLett.123.111801.
- [20] F. P. An, et al., Improved Search for a Light Sterile Neutrino with the Full Configuration of the Daya Bay Experiment, *Phys. Rev. Lett.* 117 (15) (2016) 151802. arXiv:1607.01174, doi:10.1103/PhysRevLett.117.151802.
- [21] P. Adamson, et al., Improved Constraints on Sterile Neutrino Mixing from Disappearance Searches in the MINOS, MINOS+, Daya Bay, and Bugey-3 Experiments arXiv:2002.00301.
- [22] F. An, et al., The muon system of the Daya Bay Reactor antineutrino experiment, *Nucl. Instrum. Meth. A* 773 (2015) 8–20. arXiv:1407.0275, doi:10.1016/j.nima.2014.09.070.
- [23] P. Lombardi, et al., Distillation and stripping pilot plants for the JUNO neutrino detector: Design, operations and reliability, *Nucl. Instrum. Meth. A* 925 (2019) 6–17. arXiv:1902.05288, doi:10.1016/j.nima.2019.01.071.
- [24] Q.-j. Li, Z. Wang, J.-f. Lv, X.-b. Yan, W.-q. Jiang, J.-f. Chang, Front-End Electronics system of pmt readout for daya bay reactor Neutrino Experiment, in: *Proceedings, 2009 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC 2009)*: Orlando, Florida, October 25–31, 2009, 2009, pp. 1821–1823. doi:10.1109/NSSMIC.2009.5402197.
- [25] D. Adey, et al., A high precision calibration of the nonlinear energy response at Daya Bay, *Nucl. Instrum. Meth. A* 940 (2019) 230–242. arXiv:1902.08241, doi:10.1016/j.nima.2019.06.031.
- [26] D.-M. Xia, B.-X. Yu, X.-B. Li, X.-L. Sun, Y.-Y. Ding, L. Zhou, J. Cao, W. Hu, X.-C. Ye, H.-T. Chen, X.-F. Ding, B. Du, Temperature dependence of the light yield of the LAB-based and mesitylene-based liquid scintillators, *Chinese Physics C* 38 (11) (2014) 116001. doi:10.1088/1674-1137/38/11/116001. URL <https://doi.org/10.1088/1674-1137/38/11/116001>
- [27] X. Zhou, Q. Liu, M. Wurm, Q. Zhang, Y. Ding, Z. Zhang, Y. Zheng, L. Zhou, J. Cao, Y. Wang, Rayleigh scattering of linear alkylbenzene in large liquid scintillator detectors, *Rev. Sci. Instrum.* 86 (7) (2015) 073310. arXiv:1504.00987, doi:10.1063/1.4927458.
- [28] S. Agostinelli, et al., GEANT4: A Simulation toolkit, *Nucl. Instrum. Meth. A* 506 (2003) 250–303. doi:10.1016/S0168-9002(03)01368-8.

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 299 X. R. Chen<sup>δ,33</sup>, Y. W. Chen<sup>δ,34</sup>, Y. X. Chen<sup>δ,μ,35</sup>, Y. Chen<sup>δ,μ,36</sup>, Z. Chen<sup>δ,6</sup>, J. Cheng<sup>δ,μ,6</sup>, Y. P. Cheng<sup>δ,37</sup>, Z. K. Cheng<sup>μ,36</sup>,  
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 302 C. De La Taille<sup>δ,20</sup>, F. S. Deng<sup>μ,7</sup>, J. W. Deng<sup>δ,27</sup>, Z. Deng<sup>δ,31</sup>, Z. Y. Deng<sup>δ,6</sup>, W. Depnering<sup>δ,45</sup>, M. Diaz<sup>δ,1</sup>, X. F. Ding<sup>δ,9</sup>,  
 303 Y. Y. Ding<sup>δ,μ,6</sup>, B. Dirgantara<sup>δ,46</sup>, S. Dmitrievsky<sup>δ,8</sup>, M. V. Diwan<sup>μ,19</sup>, T. Dohnal<sup>δ,μ,47</sup>, G. Donchenko<sup>δ,38</sup>, J. M. Dong<sup>δ,31</sup>, D. Dornic<sup>δ,26</sup>,  
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Statement about the “CRediT author statement”:

Due to the large number of participants in this experiment, no CRediT taxonomy has been filled in.

**Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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