







### **Update on SHELDON laboratory results**

## JUNO EU-AM collaboration meeting in Ferrara

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JUNO EU-AM 24-25 October

Università degli Studi di Milano INFN-Sezione di Milano

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## • The SHELDON project

- Measurement of fluorescence parameters
- Separation of the Cherenkov contribution
- Evaluation of the Cherenkov contribution
- Conclusion

## The SHELDON project: scientific goals

Separation of cHErenkov Light for Directionality Of Neutrino @ UNIMI - Milan Two main goals:

### Accurate measurement of

fluorescence time distribution

(fluorescence parameters)

# Study of the Cherenkov radiation in the JUNO LS

### Impact on the JUNO experiment:

- event reconstruction
- particle identification via PSD
- improved description of fluorescence parameters in the JUNO MC

### Impact on the JUNO experiment:

- Improved understanding of energy response
- Possible reconstruction of the direction of incident neutrino



JUNO LS recipe: LAB + 2.5 g/L PPO + 3.0 mg/L bis-MSB

## JUNO liquid scintillator: emission

Emission spectrum



Measured @ Università degli Studi di Perugia thanks to: Fausto, Aldo e Catia



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# JUNO liquid scintillator: absorption





Measured using a spectrophotometer in Milan

## **SHELDON:** timing measurement setup



**Components of the setup:** 

JUNO LS sample

2 PMTs, one weakly coupled

Neutral filter

2 Digitizers (5 GS/s each)

LabVIEW DAQ software

### **Technique:**

Time-Correlated Single Photon Counting

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### The SHELDON project: Impulse Response Function



## **SHELDON:** veto system



### **Components of the setup:**

2 plastic scintillators EJ 200
Linear Edge Discriminator
Coincidence Unit
3rd Digitizer (5 GS/s)
Same LabVIEW DAQ software

Delay in delivery of components  $\rightarrow$  installed in the last two weeks

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## **Measurement of fluorescence**



Alpha source fluorescence time distribution

**Fluorescence** time distribution obtained using an alpha source

Same experimental setup used in the IRF measurement

The duration of the data acquisition is 10 days to obtain 10<sup>6</sup> events

The light emission is **not** a prompt emission

# Fit model: four exponential decay



To describe the fluorescence time profile **4 components** are needed The fourth becomes

dominant starting from ~300 ns

Our DAQ time window is **1600 ns** 



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### Measurement of fluorescence parameters: α-source



### Measurement of fluorescence parameters: α-source



### Measurement of fluorescence parameters: α-source



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## Measurement of fluorescence: preliminary results

### without veto system

Measurement of **fluorescence time distribution** using three different radioactive sources.

The three curves have different tails.

We can study how our parameters impact on the JUNO MC simulation

-> Marco Malabarba's talk

	$ au_1$ [ns]	$ au_2$ [ns]	$ au_3$ [ns]	$ au_4$ [ns]
$\alpha$	4.79 ± 0.02	20.86 ± 0.39	103.8 ± 2.4	633 ± 14
p	4.60 ± 0.02	18.99 ±0.27	108.2 ± 2.1	691 ± 12
$e^-$	3.96 + 0.02	15 11 + 0.22	85.0 + 2.0	_549 ± 9
	$q_1$ [%]	$q_2$ [%]	q <sub>3</sub> [%]	$q_4$ [%]
$\alpha$	55.97 ± 0.32	23.15 ± 0.23	13.17 ± 0.16	8.50 ± 0.42
p	62.02 ± 0.27	21.07 ± 0.21	9.94 ± 0.10	6.97 ± 0.36
$e^-$	65.02 ± 0.36	23.72 ± 0.28	7.26 ± 0.10	$4.27 \pm 0.47$



## Measurement of fluorescence: preliminary results

### without veto system

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We started the measurement campain with veto and then we will share final results to the collaboration.

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## Cherenkov light can be separated from scintillation light thanks to its spectral features.

The JUNO LS emission spectrum has a maximum at 400 nm

The Cherenkov spectrum (not to scale) decreases as  $1/\lambda^2$  and extends above the scintillation spectrum.

Using appropriate optical filters it is possible to select the light in a **desired wavelength interval**, separating scintillation and Cherenkov light.



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### **Evaluation of the Cherenkov contribution**



Using the new measurement of the **refractive index** 

-> Gioele Reina's Talk

And a Geant4 simulation of our setup developed by Gioele Reina

(master student @ UNIMI)



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### **Evaluation of the Cherenkov contribution**



# Using the new measurement of the **refractive index**

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And a Geant4 simulation

of our setup

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### **Evaluation of the Cherenkov contribution**



### We will measure the Cherenkov contribution in the JUNO LS comparing real data with simulations

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# **Conclusions (1)**

- We developed an experimental setup for the fluorescence time measurement
- We produced the JUNO liquid scintillator and measured the emission spectrum
- We measured the fluorescence distribution with three radioactive sources
- We are improved the setup with a muon veto
- We are measuring the Cherenkov contribution at different wavelength



# **Conclusions (2)**

- we stress the need of creating a database with the different sets of parameters and an ID for each set (to be included in SNIPER) → talk to AFG soon
- we will discuss the consistency of our analysis with other people involved in similar measurements → during this meeting
- we plan to finalize a paper on this measurements  $\rightarrow$  in the very next weeks

		short title of the p	aper for running head	short title of the	saper for narring head	short title of the p	aper for nurning head	short title of the	paper for running head
High accuracy measure	ment of fluorescence narameters in liquid	Table 1	The absorption of the scintillator mixture was measured		cuvette and the PMT to further reduce the optical coupling to		DecayTime	DesayTime	DecayTime
		Composition of LAB-based scintillators used in past, present	with respect to a blank obtained with henane.	Absorption & Errission	the liquid scintillator. To ensure the single-photon condition	Test and the second	2070)	The second secon	An Internet
organic scintillators		and future experiments.	3.2 Manufacture	· Oncorr	we always used a NDUVINA neutral density optical filter		Andreas PERSON No. 200 NO. 10 NO.	- Annual Contraction	8 Mar - Horney Park Andrew States
		Mieture PPO (g/L) bis-M58 (rg/L)	We measured the emission spectrum of the JUND liquid		(optical density: 1.3). The curvette is enclosed in an abarringer frame and a can	A	S	UP BALLON CH MALLON	UN ANTIN
		DB/SABRE 3 15	scintillator between 250 nm and 600 nm. The resulting	3 cent	closes its open face on top. The cap is provided with a needle	All Man and		A Des marcan	TEA Set Theorem
ARTICLE INFO	ABSTRACT	JUNO 2.5 3	spectrum is visible (in Nack) in figure 1. In the same figure	Î ·····	that goes all the way into the liquid scintillator and allows		Street and Street and Street	W MALLER AND	and the second s
Ensurate	I be define a set of the second second in a second se	580+ 2 -	are visible the emission spectra of pure LAB (in blue), of	i cons Y	nitrogen babbling. Nitrogen babbling has preven to be ef-	20 I I I I I I I I I I I I I I I I I I I		UN MALEN	UNI MONTE
scatilatos, flaorescence, Cheverkey,	wildively high fight yield and good faming properties. Along with scintillation light, a charged particle		(in error). All of the spectra in figure 1 are normalized to the	I. M	Sective in reducing quenching caused by oxygen dissorved in Xerial criatellators Landors et al. (2012). Gaussian addresses		Million Contraction of Contraction o	Company and and an and a second	Nor President delegated teacher
150	moving in the scattilizator can produce a certain amount of Chervaliov tight, provided that the speed of the characel particle is above threshold. Since Chervaliov light is emitted instantaneously as the charaed	The composition of the scintillator mixture determines	maximum to better appreciate the differences in their shape.		comes to the needle from a small tube provided with an	And in case of the second seco			
	particle moves in the medium, it can affect the measurement of the characteristic fluorescence times	its properties, including the time distribution of fluorescence	The peak at 265 nm is caused by diffusion of incident light		entrance valve, bubbles in the liquid scintillator and gets out	** m	PMD 46	and the second s	Harris - Berger - Start Stranger
	Here we prove that the contribution of Chevenkov light, as well as a sufficient duration of the	contributions used to describe flaorescence liebt and their		com	of the cuvette passing through a small hole and a tube with			1410	and a
	acquisition window must be considered to perform accurate measurements of the theoreticence times	relative importance.	слажот кристи	300 210 410 400 100 300 MD Viewingto (see	The blockbox is resilianed between two plastic usin-	H	N N 10 12 12 13 12 12 12 19 10 10 10 10	(a) Beta	(b) Neutrons
	scinillator minure that will be used in the IUNO experiment with a thoroughly characterized small-	In this work we report on the measurements obtained for	5 4 A A A A A 🗮 🚟		tillater modules placed immediately above and below the	(1) 201	do Mala	Decayine (714 (25-0114)	LectyTitle
	scale series. Our study will allow improved Pulse Shape Discrimination in JUND as well as in other reconstruction to the study of the	the scintillator mixtures summarized in table 1 The motures	A NA AN I THE	Figure 2: Absorption spectra of the motures.	blackbox to veto the events caused by cosmic-ray induced			and the second	1 13
	obtained and the generation about communer	were prepared starting from the single components, moong	64 N N N N N N N N N N N N N N N N N N N		maons passing through them. Each module is composed by			in manager MPH CAG(1100) Nathanian Mathematical Mathematical	
	Annual forme substitutions Sada as descend stratistic stration	a suitably small volume of scintillator to be used in our	on 1	We note that self-absorption of emitted light is non-	a slab of EJ-200 (500 mm × 500 mm × 20 mm) wrapped in orthoctics foil, and could be a block sized both tight container.	4.2. Measurement of the Buorescence time distribution	Thanks to the linearity of the operation, the analytic conso- lation of the IRE with the flavour and a model in equation 1	101 101 101 101 101 101 101 101 101 101	*1
1. Introduction	Apart from scintillator can also cause the emission of Cherenkov	measurements, of the order of 100 ml, PPO was weighted		negligible below 400 nm. This motivates the front-face	and coupled to a 25 mm PMT at one angle.	The time distribution of the flavorescence light emitted by	2005	L N MALLER	
Scintillation consists in a process th	adiation, depending on the speed of the particle itself and	with a precision scale and directly added to the LAB. To in-	eff N/ V	method used for measurement of the emission spectrum, that	Signals coming from the PMTs facing the liquid scin-	the scintillator can be described by the superposition of some		State State	and the second sec
part of the energy deposited by char-	the refractive index of the scintillator. Cherenkov light is	citize no-MSB is the moures, a master solution containing his MSB and LAB (1.30000) and reasoned to control the		would otherwise be affected by absorption, resulting both in a underestimation of the construct in the posing of chorter	tillator are digitized by 2 separate NI PXIe-5162 digitizers	exponential distributions. Given our 1600 ns long acquisi-	$n = m = n \sum_{i=1}^{d} \sum_{j=1}^{2} n_{i} n_{j} (a) (a) (n = a) (1 + a) (n = a)$	No. Contraction of the second	THE REAL PROPERTY AND INCOME.
scintillator, it causes the excitation of	electrons in the e-	amount of bis-MSB with higher accuracy and was added to	"R L	wavelength and in a overestimation in the region at length	(10 bit, 5 GNs, 1.5 GEt) included in a NI PXIe-1075	tion window, we modeled the time distribution of emitted	$F_{fher}(t) = N \sum_{d=1}^{N} \sum_{i=1}^{N} N_{d} N_{j} (e^{-i/4} - e^{-i/4}) + O_{j}(t; \mu_{j}, \theta_{j})$		
bonds of solvent molecules Knoll (2	(18). Electrons can this light is absorbed by the scientifiator and subsequently	the mixtures to reach the correct volume of LAB and the		wavelength.	Signals coming from the vote modules have through a NIM	alger with four effective components. Such a choice has already been motivated in measure literature, which meatly	(4)		
populate different excited states, that	enactedy decay non- re-emitted isotropically in the form of flaorescence light.	desired amount of his-MSB. A complete description of the	and the state of the state of		coincidence unit whose output is digitized by a third NI	describes the LAB-based scintillators with four exponential		The second secon	The take and take take take take take take
radiatively to the first excited singlet stat the order of a set. The first excited singlet	e (typical ideanie of Nevertheless, long-wavelength Cherenkov light above the	procedures followed to propare the sourcitator motores can be found in Researce (2022).	Reviewph (w)	4. Timing properties	PXIo-5162. The digitizers are operated in interleaving mode	components ?. Thanks to the high resolution of our setup,	where the $N_f$ is the normalization of the flaorescence con-	(c) Abda	AD Contine
the ground state emitting flacerscence l	absorption spectrum of the scintillator does not get absorbed	the sound in section (sound).	Figure 1: Emission spectra of the scintillator mixture and of	Once the emission and absorption spectra of the lia	to fully exploit their capabilities and use the highest possible	we were able to observe the rising edge of the light signal	weights of the server Gaussian functions and N is the total	(c) reprint	(c) capace
of the order of few ns to hundreds of a	s). The first excited of emitted liefs as already pointed out in []	1 Emission and abcomption spectra	its components.	uid scintillator are known, the timing properties can be	sampung rate.	and this had to be taken into account in our analysis. The resulting distribution can be written as	number of entries in the histogram.	Figure	e 4: Caption
singlet state can also decay to the first	excited triplet state Neglecting the contribution of Cherenkov light causes	Contrast and another and spectra		investigated in a dedicated setup, using radioactive sources	4.1.1. Impulse Response Function	· · · · · · · · · · · · · · · · · · ·	Cherenkov radiation is emitted with characteristic time		
which subsequently decays to the gr	and state centing an error in the determination of the timing properties of the	M. Setup	and the peak at 530 mm is due to the second harmonic present	Charged particles travelling in the sentillator do not only	The Impulse Response Function (IRF) of the entire	$E_{\mu} = N \sum_{i=1}^{n} \frac{d_{\mu}}{d_{\mu}} \left( e^{\frac{1+q_{\mu}}{2}} - e^{\frac{1+q_{\mu}}{2}} \right) \Theta(-1) (0)$	shorter than the resolution of our setup so we model it as	BRD and an and	and the second sec
Alternatively, escited states can rela-	to the errord state scintillator and does not allow to exploit its full potential.	measured using a Spea Fluorolog-2 [680/] spectrulino-	In the beam of incident light. As of today, this is the first menomement of the emission	the emission of Cherrekey light, depending on their velocity	system has been measured using a public laser source with 25 m m for milds and a membranith of 205 mm. The boot user	$r_{fil} = r_{fil} \sum_{d=1}^{l} \frac{r_d - r_d}{r_d - r_d} \left( r_{fil} - r_{fil} + r_{fil} \right) \left( r_{fil} - r_{fil} \right)$	in impuse distribution, just the Cherenkov contribution has to be controlated with the IRE and the time distribution	+ p	an annear constance, data solar angli al anno j sana antis ansar.
non-radiatively, coenching the emission	of light, Molecules Moreover, the separation of Cherenkov light can provide	rimeter, controlled by the Spex Datamax spectroscopy soft-	spectrum of the RUNO liquid scintillator misture. This spec-	and the refractive index of the scintillator. If Cherenkov	75 ps plane what i and a wavelength or 405 mm. The later was counted to an optical fiber opporting the black host permission	where N is a normalization constant, as and rs are the	of emitted light is a weighted sam of facerscence 1 and		
in the first excited triplet state can a	to go back to the correlated to the direction of the incention rentring	ware, similarly to what was described in Lombardi, Ortica,	trum is very similar to the emission spectrum of bis-MSB,	light is emitted, its contribution must be considered in the	with a Teffon diffuser. The light scattered from the diffuser,	relative weights (also called fractions hereafter) of the d-th	Cherenkov äght:		
first excited singlet state because of the	rmal excitation and	Ranacci and Romani (2013). The excitation light was pro-	however, some other peculiar features are present at 400 nm	measurement of the timing properties of the scintillator	conveniently attenuated by means of some optical filters,	component and its characteristic decay times, r, is the char-	and the second second second second		
To movent arlicohormion of scini	Inter lists cannot 2. Composition and properties of the liquid	obtain a beam with wavelength of 265 nm on the sample.	and below, in particular, the peak at 400 mm is relatively	and study the contribution of Cherenkov light thurks to it	mitraicks the emission from the scintillator and is sufficiently	acteristic rise time (common to all the four components) and file documentation for much adapted of the float	$F_{Taud}(t) = [N_{Ch}\delta(t, t_h) + (1 - N_{Ch})F_{Tau}(t)] +  BP(t) $		
by the superposition of emission and	absorption spectra scintillators	Both the excitation and the emission monochromators were	are present at about 340 nm and 360 nm that are not visible	timing features.	counted PMT, art aufficiently bright to cause the strength.	time profile. The normalization of the fourth component	(5)	11 /	
of the organic solvent, a second comp	ment usually called Linear alta became if All) has become one of the best	set to have a bandwidth of 1.5 mm.	in the bis-MSB emission spectrum. The peak	The time distribution of fluorescence light emitted by the	coupled PMT to trigger the acquisition. To better emulate the	requires a particular treatment due to the acquisition time	where N <sub>CB</sub> is the fraction of Cherenkov light with respect to	3	
"scintillation floor" is added in small fr	actions. The solvent available solvents lately, thanks to its good safety features,	The measurements were performed in front-face geom-	The peak at about 290 nm, due to light emission by LAB,	liquid scintillator is can be modeled with a superposition of	effect of refraction and reflections, the diffuser was placed	window, which is limited to 1.6 µs. This limitation implies a	total emission (Cherenkov and flaorescence).	TE /	
subscenatile arrity factorearce. Each	in a mation centride high transparency, material compatibility and low cost.	direction. In this configuration the incident light with a sume-	vanishes when PPO is present in the mastare because of	constant exponential and matters with characteristic time	inside a cuvette containing pure LAB and covered with	truncation in the light collection, so the normalization of the	(3) Departmention	TE /	
the absorption spectrum of the solvent.	To further improve These features were already considered for the Doya Bay	length of 265 nm is absorbed in about 10 micrometers and	rm in the spectrum of the mixture composed by LAB + 0.1	contains and reading weight billings (1964).	an automation too, so that the conditions were in case in movible to the real measurement In Considered the dead	South exponential component $\frac{1}{\tau_{e}-\tau_{e}}$ needs to be corrected.	5. Palse Shane Discrimination	Laurania	
transparency in large detectors and pro	vide a better match experiment [] and were pivolal in the choice of LAB-	self-absorption of flaorescence light emitted in the direction	pkg bis-MSB (in green in figure 1) is a residual of light	4.1. Setup	time of the digitizers, the period of the loser (20 as) has been	$1 = \nabla^3$ , $\alpha$ ,	te i and ompe population	<sub>Um</sub>	
with photomaltiplier tabes (PMTs), a t	ind component can experiments such as RUNO [], SNO+[] and SABRE[].	of the detector is negligible.	emission by LAB, parily absorbed by bin-MSB.	The setup for the measurement of the timing leature	chosen to have the highest counting rate.	$q_1 = -\frac{M_{111} + m_1}{m_1 + m_2}$ (2)	6. Conclusions	Free f. H. fly	
be added in even smaller intenses, the	varieting in territer. 2,5 diphenyloxazole (PPO) was chosen as primary scin-	account thirds to a measurement with a Bhudomine cali-	The peak at 550 nm in all spectra correspond to the second horizonia in the excitation have and is not a feature	composed by a cruette made of optical class filled with the	We measured the IRF placing the diffuser in three differ-	1-e 1	Acknowledgements	right is training	
ponents in the minture, the time distrib-	tion of scintillation flaor in these new experiments with a concentration	bration standard in the spectral region between 250 nm and	of the scintillator.	liquid scintillator mixture and two PMTs facing the cuvetle	on position more the covere to study the different effect	where $r_{g} = 1600$ as is the length of the DAQ time window.	7.		
light can be effectively described by the	Inear combination of 2.5 g/L, 2.g/L and 3.g/L respectively. Moreover, JUNO and SABPE will also use 1.4-Bit/2-methodatory/documents	600 nm. Each point in the spectrum is normalized to the	We measured the absorption spectrum of different sam-	inside a black box. One PMT (model R1828-01) is part of an	The IRF has been fitted using a superposition of 7 Gaus-	The tight uncotlected because of the finite duration of our	References	Januaries and a second state of the second s	
of a certain number of exponential con	tributions, each one (bis-MSB) with concentrations of 3 mg/L and 15 mg/L	escatation light intensity, thanks to a beam splitter and a	ples, as reported in figure 2: pare LAB (in blue), LAB + 2.5	asseminy (H1949-51) including a magnetic shield and face the curvets in close meanatry, so that its optical counties to	sian distributions, which is a reasonable trade-off between	To take into account the finite resolution of the setup it	Brants M. 2022 Insurand measurement of timing and cation another	dataseys (1964) arg/18.301(101)-9-46-838(1)-9.588(1)-6. Kwill, G.F., 2019. Radiation detection and measurement. J <sup>(2)</sup> ed. WILEY.	
where a constant work of the cost of the stat is to	respectively to further increase the light yield and match	The absorption spectra of the scittillator minture was	pt. PPO (in real, LAB + 0.1 pag 06-MSB (in pree) and the minimum that will be used in ILINO 1 AB + 2.5 all 1980	the hand scintillator is very strong. A second PMT (mode	the most simple and the most accurate description of its different features	is necessary to convolve the flaorescence model described in	of the RNO scintillance Manne's thesis. University of Milan-	Lombark, P., Orice, F., Ramovi, G., Romani, A., 2013. Decay time an	à
"Concepteding author	the emission spectrum of the scintillator with the efficiency	measured using a Jasco V-760 Spectrophotometer provided	+ 3 mg/L bis-MSB (in black). All of the absorption spectra	R4220P) is a side-window PMT optimized for single-photon	VALUE AND ADDA.	equation 1 with the IRF:	BRKS, J., 1964. Chapter 8 - organic liquid scintillators, in: BRKS, J. (Ed.). The Theory and Bustiss of Acadibidius	pulse shape discrimination of liquid scinithions based on novel sol years. Nuclear Instruments and Methods in Physics Economy Society &	
	ORVEOUND ENDS.	with a LSE-T01 Single Position Long Path Length (maxi-	in figure 2 have been shifted to have the same minimum.	counting opplications. This latter faces the curvette in fac		$(f = 2)0 = \int_{-\infty}^{\infty} (g_2 - g_3) dg_3 = -g_3$	Counting: Pergamon. International Series of Monographs in	Accelerators, Spectromaters, Detectors and Associated Equipment 781	
		mum: 100 mm) Cell Holder.		geometry and different filters can be positioned between the		$O = grou = \int_{-\infty} f(r)gr = r dr$ (3)	Entronics and Instrumentation, pp. 305-330. URL: https:/	135-144. URL: https://www.acianostirect.cos/acticle/oil	
High accuracy measurement of Russesses	on parameters in liquid organic scietillators: Proprio submissof to Election Page 1 of 5	High accuracy measurement of fluorescence parameters in liqui	id arganic scietiflators: Preprint submitted to Elization Page 2 of 5	High accuracy measurement of fluorescence parameters in liq	id organic scietillators: Proprior submitted to Elsevier Page 3 of 5	High accuracy measurement of fluorescence parameters in liqu	id organic scintillature: Proprint submitted to Elsevier Page 4 of 5	High accuracy measurement of fluorescence parameters in Fig	uid arganic scintillators: Preprint submitted to Elsevier Page 5 of 5

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### High accuracy measurement of fluorescence parameters in liquid organic scintillators

#### ARTICLE INFO

#### ABSTRACT

Keywords: scintillation, fluorescence, Cherenkov, PSD Liquid organic scinillators are widely used in experimental nuclear and particle physics thanks to their relatively high light yield and good timing properties. A long with scinitillation light, a charged particle moving in the scinillator can produce a certain amount of Cherenkov light, provided that the speed particle moves in the medium, it can affect the measurement of the characteristic fluorescence times of the scinitistic and the relative contribution of each fluorescence times of the scinitistic and the relative contribution of each fluorescence times of the scinitistic and the relative contribution of each fluorescence times of

Here we prove that the contribution of Cherenkov light, as well as a sufficient duration of the acquisition vindow must be considered to perform accurate measurements of the fluorescence times and their relative importance. Moreover, we report on a new measurement of the parameters of the simillator mixture that will be used in the UNO experiment with a thoroappily characterized smallscale setup. Our study will allow improved Pulse Shape Discrimination in JUNO as well as in other experiments using LAB-based liquid oranic scintillators.

#### 1. Introduction

Scintillation consists in a process that converts into light part of the energy deposited by charged particles in the scintillator. In fact, as a charged particle moves in an organic scintillator, it causes the excitation of electrons in the  $\pi$ bonds of solvent molecules Knoll (2018). Electrons can populate different excited states, that quickly decay nonradiatively to the first excited singlet state (typical lifetime of the order of a ps). The first excited singlet state then decays to the ground state emitting fluorescence light (typical lifetime of the order of few ns to hundreds of ns). The first excited singlet state can also decay to the first excited triplet state which subsequently decays to the ground state emitting phosphorescence light (typical lifetime of the order of ms). Alternatively, excited states can relax to the ground state non-radiatively, quenching the emission of light. Molecules in the first excited triplet state can also go back to the first excited singlet state because of thermal excitation and generate delayed fluorescence.

To prevent self-absorption of scintillation light caused by the superposition of emission and absorption spectra of the organic solvent, a second component usually called "scintillation fluor" is added in small fractions. The solvent transfers energy to the fluor (mainly non-radiatively), which subsequently emits fluorescence light in a region outside the absorption spectrum of the solvent. To further improve transparency in large detectors and provide a better match with photomultiplier tubes (PMTs), a third component can be added in even smaller fractions, the wavelength shifter

As a result of the excitation and de-excitation of the components in the mixture, the time distribution of scintillation light can be effectively described by the linear combination of a certain number of exponential contributions, each one with a characteristic decay time and a relative weight.

\*Corresponding author ORCID(s): Apart from scintillation light, a charged particle moving in the scintillator can also cause the emission of Cherenkov radiation, depending on the speed of the particle itself and the refractive index of the scintillator. Cherenkov light is emitted instantaneously, is directional and its spectrum decreases as  $\lambda^{-2}$  (where  $\lambda$  is the wavelength). A large part of this light is absorbed by the scintillator and subsequently re-emitted isotropically in the form of fluorescence light. Nevertheless, long-wavelength Cherenkov light above the absorption spectrum of the scintillator does not get absorbed and contributes to the very first part of the time distribution of emitted light, as already pointed out in [].

Neglecting the contribution of Cherenkov light causes an error in the determination of the timing properties of the scintillator and does not allow to exploit its full potential. Moreover, the separation of Cherenkov light can provide information on the direction of scattered electrons, which is correlated to the direction of the incoming neutrino.

#### 2. Composition and properties of the liquid scintillators

Linear alkylbenzene (LAB) has become one of the best available solvents lately, thanks to its good safety features, high transparency, material compatibility and low cost. These features were already considered for the Daya Bay experiment [] and were pivotal in the choice of LABbased liquid scintillators in a new generation of rare event experiments use has JUNO II. SNO+II and SABREII.

2.5-diphenyloxazole (PPO) was chosen as primary scintillation fluor in these new experiments with a concentration of 2.5 g/L, 2.g/L and 3.g/L respectively. Moreover, JUNO and SABRE will also use 1.4-Bis(2-methylstyryl)benzene (bis-MSB) with concentrations of 3 mg/L and 15 mg/L respectively to further increase the light yield and match the emission spectrum of the scintillator with the efficiency curve of the PMTs. Table 1 T Composition of LAB-based scintillators used in past, present with and future experiments.

Mixture	PPO (g/L)	bis-MSB (mg/L)
DB/SABRE	3	15
JUNO	2.5	3
SNO+	2	-

The composition of the scintillator mixture determines its properties, including the time distribution of fluorescence light, the characteristic time of the different exponential contributions used to describe fluorescence light and their relative importance.

In this work we report on the measurements obtained for the scintillator mixtures summarized in table 1 The mixtures were prepared starting from the single components, mixing them in the appropriate volumetric fractions. To prepare a suitably small volume of scintillator to be used in our measurements, of the order of 100 ml, PPO was weighted with a precision scale and directly added to the LAB. To include bis-MSB in the mixtures, a master solution containing bis-MSB and LAB (1:10000) was prepared to control the amount of bis-MSB with higher accuracy and was added to the mixtures to reach the correct volume of LAB and the desired amount of bis-MSB. A complete description of the procedures followed to prepare the scintillator mixtures can be found in Bereta (2022).

#### 3. Emission and absorption spectra

#### 3.1. Setup

The emission spectra of the scintillator mixtures was measured using a Spex Fluorolog-2 1680/1 spectrofluorimeter, controlled by the Spex Datamax spectroscopy software, similarly to what was described in Lombardi, Ortica, Ranucci and Romani (2013). The excitation light was produced by a Xenon discharge lamp and monochromated to obtain a beam with wavelength of 265 nm on the sample. Both the excitation and the emission monochromators were set to have a bandwidth of 1.5 nm.

The measurements were performed in front-face geometry at an angle of  $22^{\circ}$  with respect to the incident light direction. In this configuration the incident light with a wavelength of 265 nm is absorbed in about 10 micrometers and self-absorption of fluorescence light emitted in the direction of the detector is negligible.

The quantum efficiency of the detector is taken into account thanks to a measurement with a Rhodamine calibration standard in the spectral region between 250 nm and 600 nm. Each point in the spectrum is normalized to the excitation light intensity, thanks to a beam splitter and a reference detector.

The absorption spectra of the scintillator mixture was measured using a Jasco V-760 Spectrophotometer provided with a LSE-701 Single Position Long Path Length (maximum: 100 mm) Cell Holder. The absorption of the scintillator mixture was measured with respect to a blank obtained with hexane.

#### 3.2. Measurements

We measured the emission spectrum of the JUNO liquid scintillato between 250 nm and 600 nm. The resulting spectrum is visible (in black) in figure 1. In the same figure are visible the emission spectra of pure LAB (in blue), of LAB  $\pm 2.5 gL$  PPO (in red) and of LAB  $\pm 0.1 gK$  bis-MSB (in green). All of the spectra in figure 1 are normalized to the maximum to better appreciate the differences in their shape. The peak at 256 nm is caused by diffusion of incident light

Emission spectra



Figure 1: Emission spectra of the scintillator mixture and of its components.

and the peak at 530 nm is due to the second harmonic present in the beam of incident light.

As of today, this is the first measurement of the emission spectrum of the JUNO liquid scintillator mixture. This spectrum is very similar to the emission spectrum of bis-MSB, however, some other peculiar features are present at 400 nm and below. In particular, the peak at 400 nm is relatively more important in this spectrum and other two lower peaks are present at about 340 nm and 360 nm that are not visible in the bis-MSB emission spectrum. The peak

The peak at about 280 nm, due to light emission by LAB, vanishes when PPO is present in the mixture because of absorption by PPO. The structure between 320 nm and 350 nm in the spectrum of the mixture composed by LAB + 0.1 g/kg bis-MMB (in green in figure 1) is a residual of light emission by LAB, partly absorbed by bis-MMSB.

The peak at 530 nm in all spectra correspond to the second harmonic in the excitation beam and is not a feature of the scintillator.

We measured the absorption spectrum of different samples, as reported in figure 2: pure LAB (in blue), LAB + 2.5 g/L PPO (in red), LAB + 0.1 g/kg bis-MSB (in green) and the mixture that will be used in JUNO, LAB + 2.5 g/L PPO + 3 mg/L bis-MSB (in black). All of the absorption spectra in figure 2 have been shifted to have the same minimum.

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Figure 2: Absorption spectra of the mixtures.

We note that self-absorption of emitted light is nonnegligible below 400 nm. This motivates the front-face method used for measurement of the emission spectrum, that would otherwise be affected by absorption, resulting both in a underestimation of the spectrum in the region at shorter wavelength and in a overestimation in the region at longer wavelength.

#### 4. Timing properties

Once the emission and absorption spectra of the liquid scintillator are known, the timing properties can be investigated in a dedicated setup, using radioactive sources. Charged particles travelling in the scintillator do not only cause the emission of scintillation light, but can also cause the emission of Cherenkov light, depending on their velocity and the refractive index of the scintillator. If Cherenkov light is emitted, its contribution must be considered in the measurement of the timing properties of the scintillator. Here we describe the techniques that we used to separate and study the contribution of Cherenkov light thanks to its timing features.

The time distribution of fluorescence light emitted by the liquid scintillator is can be modeled with a superposition of different exponential distributions with characteristic time constants and relative weigth BIRKS (1964).

#### 4.1. Setup

The setup for the measurement of the timing features of the light emitted by the liquid scintillator is basically composed by a cuvetle made of optical glass filled with the liquid scintillator mixture and two PMTs facing the cuvetle inside a black box. One PMT (model R182A-01) is part of an assembly (H1949-51) including a magnetic shield and faces the cuvette in close geometry, so that its optical coupling to the liquid scintillator is very strong. A second PMT (model R4220P) is a side-window PMT optimized for single-photon counting applications. This latter faces the cuvette in far geometry and different filters can be positioned between the cuvette and the PMT to further reduce the optical coupling to the liquid scintillator. To ensure the single-photon condition we always used a NDUV13A neutral density optical filter (optical density: 1.3).

The cuvette is enclosed in an aluminum frame and a cap closes its open face on top. The cap is provided with a needle that goes all the way into the liquid scintillator and allows nitrogen bubbling. Nitrogen bubbling has proven to be effective in reducing quenching caused by oxygen dissolved in liquid scintillators Lombardi et al. (2013). Gaseous nitrogen comes to the needle from a small tube provided with an entrance valve, bubbles in the liquid scintillator and gets out of the cuvette passing through a small hole and a tube with an exit valve.

The blackbox is positioned between two plastic scintillator modules placed immediately above and below the blackbox to veto the events caused by cosmic-ray induced muons passing through them. Each module is composed by a slab of EJ-200 (500 mm  $\times$  20 mm) wrapped in reflective foil, enclosed in a black vinyl light-tight container and coupled to a 25 mm PMT at one anale.

Signals coming from the PMTs facing the liquid scintillator are digitized by 2 separate NI PXIe-5162 digitizers (10 bit, 5 GSk, 1.5 GH2) included in a NI PXIe-1075 chassis controlled by a NI PXIe-8103 embedded controller. Signals coming from the veto modules pass through a NIM coincidence unit whose output is digitized by a third NI PXIe-5162. The digitizers are operated in interleaving mode to fully exploit their capabilities and use the highest possible sampling rate.

#### 4.1.1. Impulse Response Function

The Impulse Response Function (IRF) of the entire system has been measured using a pulsed laser source with 75 ps pulse width and a wavelength of 405 nm. The laser was coupled to an optical fiber entering the black box, terminated with a Teflon diffuser. The light scattered from the diffuser, conveniently attenuated by means of some optical filters, mimicks the emission from the scintillator and is sufficiently faint to fulfill the single-photon condition in the weaklycoupled PMT, yet sufficiently bright to cause the stronglycoupled PMT to trigger the acquisition. To better emulate the effect of refraction and reflections, the diffuser was placed inside a cuvette containing pure LAB and covered with an aluminum foil, so that the conditions were as close as possible to the real measurement 3a. Considered the dead time of the digitizers, the period of the laser (20  $\mu$ s) has been chosen to have the highest counting rate.

We measured the IRF placing the diffuser in three different positions inside the cuvette to study the different effect of refraction and reflections 3b.

The IRF has been fitted using a superposition of 7 Gaussian distributions, which is a reasonable trade-off between the most simple and the most accurate description of its different features.

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#### 4.2. Measurement of the fluorescence time distribution

(a) Beta

The time distribution of the fluorescence light emitted by the scintillator can be described by the superposition of some exponential distributions. Given our 1600 ns long acquisition window, we modeled the time distribution of emitted light with four effective components. Such a choice has already been motivated in previous literature, which mostly describes the LAB-based scintillators with four exponential components?. Thanks to the high resolution of our setup, we were able to observe the rising edge of the light signal and this had to be taken into account in our analysis. The resulting distribution can be written as

$$F_{fit} = N \sum_{d=1}^{4} \frac{q_d}{\tau_d - \tau_r} \left( e^{-\frac{t-t_0}{\tau_d}} - e^{-\frac{t-t_0}{\tau_r}} \right) \Theta(t - t_0)$$
(1)

where N is a normalization constant,  $q_d$  and  $\tau_d$  are the relative weights (also called fractions hereafter) of the *d*-th component and its characteristic decay times,  $\tau_r$  is the characteristic rise time (common to all the four components) and  $\Theta$  is the step function that marks the start of the fluorescence time profile. The normalization of the fourth component requires a particular treatment due to the acquisition time window, which is limited to 1.6 µs. This limitation implies a truncation in the light collection, so the normalization of the fourth exponential component  $\frac{1}{\tau_{cr}}$  needs to be corrected:

$$q_4 = \frac{1 - \sum_{d=1}^{3} q_d}{1 - e^{-\frac{l_W - l_0}{r_4}}}$$

where  $t_w = 1600$  ns is the length of the DAQ time window. The light uncollected because of the finite duration of our acquisition window is about 9.1% of the fourth component

To take into account the finite resolution of the setup it is necessary to convolve the fluorescence model described in equation 1 with the IRF:

$$(f * g)(t) = \int_{-\infty}^{\infty} f(\tau)g(t-\tau)d\tau$$

Thanks to the linearity of the operation, the analytic convolution of the IRF with the fluorescence model in equation 1 gives

$$I_{luo}(t) = N \sum_{d=1}^{4} \sum_{j=1}^{7} N_d N_j \left( e^{-t/\tau_d} - e^{-t/\tau_r} \right) * G_j(t; \mu_j, \sigma_j)$$
(4)

where the  $N_{ij}$  is the normalization of the fluorescence component, as discussed before, the  $N_{ij}$  are the normalized weights of the seven Gaussian functions and N is the total number of entries in the histogram.

Cherenkov radiation is emitted with characteristic time shorter than the resolution of our setup so we model it as an impulse distribution. Also the Cherenkov contribution has to be convolved with the IRF and the time distribution of emitted light is a weighted sum of fluorescence 1 and Cherenkov light:

$$F_{Total}(t) = \left[N_{Ch} \,\delta(t, t_0) + (1 - N_{Ch}) F_{Fluo}(t)\right] * \text{IRF}(t)$$
(5)

where  $N_{Ch}$  is the fraction of Cherenkov light with respect to total emission (Cherenkov and fluorescence).

4.3. Uncertainties 5. Pulse Shape Discrimination

6. Conclusions

#### Acknowledgements

7

(2)

(3)

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High accuracy measurement of fluorescence parameters in liquid organic scintillators: Preprint submitted to Elsevier Page 4 of 5

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Figure 4: Caption



Figure 5: BlaBla

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Knoll, G.F., 2018. Radiation detection and measurement, 4<sup>th</sup> de Unburdt, P., Ortica, F., Ranucci, G., Romani, A., 2013. Decay time and pulse shape discrimination of liquid scintillators based on novel solvents. Nuclear Instruments and Methods in Physics Research Section X: Accelerators, Spectrometers, Detectors and Associated Equipment 701, 133-144. URL: https://www.sciencedirect.com/science/article/pi1/

### To be concluded very soon...

# Thank you Questions?

# Backup

# **Cosmic background in SHELDON**



We have measured the rate of cosmic muons detected by our setup without any radioactive source

We have determined the fluorescence parameters associated to this distribution

### Monte Carlo study

# **Cosmic background**



We have measured the rate of cosmic muons detected by our setup **without** any radioactive source

We have determined the fluorescence parameters associated to this distribution

We have evaluated the impact of this background in our measurement using simulations

# Fit model: Cherenkov contribution



# The Cherenkov contribution is modeled as a **delta function**

It is summed to the **fluorescence** model

(1)1

The **sum** is convolved with the detector response

IRF(t) = 
$$\sum_{j=1}^{7} N_j G_j(t; \mu_j, \sigma_j)$$

$$F_{Fluo}(t)] * IRF(t)$$

TD TI()



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### The SHELDON project: Impulse Response Function

Normalized couts

Diffuser **HL PMT** LS sample 0 Neutral filter + LL PMT Optical fiber

The measurement of the Impulse Response Function is performed using a laser.

The laser has a pulse duration of 75 ps.

A diffuser is placed at the end of the optic fibre to mimic a point like emission





### Monte Carlo study

# **Method validation**

### Monte Carlo simulation to produce 10<sup>4</sup> fake dataset

used to evaluate the **possible fit sistematics** on fluorescence parameters



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# **Method validation**

**Monte Carlo** 

study

The uncertainties on the fluorescence parameters are at the percentage level



# Monte-Carlo study Systematic error introduced by the choice the DAQ time window

The relative uncertainty on slow component decreases as the upper end of the DAQ time window increases.



Tau4 relative error on DAQ time window

The red line represent our DAQ time window

The number of events is fixed (similar to a measurement lasting **one week**)

As the statistic increases the uncertainty decreases

The trend does not change with increasing statistics

## Measurement of fluorescence: Results

	$ au_1$ [ns]	$ au_2$ [ns]	$ au_3$ [ns]	$ au_4$ [ns]	$ au_r$ [ns]
α	4.79 ± 0.02	$20.86 \pm 0.39$	103.8 ± 2.4	633 ± 14	0.832 ± 0.002
p	$4.60 \pm 0.02$	18.99 ±0.27	108.2 ± 2.1	691 ± 121	1.208 ± 0.001
$e^-$	$3.96 \pm 0.02$	15.11 ± 0.22	85.0 ± 2.0 -	U 549 ± 9	$1.667 \pm 0.001$
	$q_1$ [%]	q <sub>2</sub> [%]	TS B [%]	$q_4$ [%]	$\chi^2_r$
α	55.97 ± 0.32	23.15 ± 0.23	13.17 ± 0.16	8.50 ± 0.42	1.38
p	62.02 + 9.27	21.07 ± 0.21	9.94 ± 0.10	6.97 ± 0.36	1.4
$e^-$	65.02 ± 0.36	23.72 ± 0.28	7.26 ± 0.10	4.27 ± 0.47	1.35

# Measurement of fluorescence: Results

Particles	Fast(ns)/ Ratio	Slow(ns)/ Ratio	Slower(ns)/ Ratio	Slowest(ns)/ Ratio
$\gamma, e^+, e^-$	4.6/70.7%	15.1/20.5%	76.1/6.0%	397/2.8%
$n, p^+$	4.5/61.4%	15.7/23.2%	76.2/9.0%	367/6.4%
α	4.345/49.82%	17.64/27.39%	89.045/14.67%	544.48/8.12%

### Talk of Yaoguang Wang "Detector simulation status" 18/07/2022

e⁻	3.96/65.02%	15.11/23.72%	85.0/7.26%	549/4.27%
р	4.60/62.02%	18.99/21.07%	108.2/9.94%	691/6.97%
α	4.79/55.97%	20.86/23.15%	103.8/13.17%	633/8.50%

## **Determination of the Cherenkov spectrum**



# Using the new measurement of the **refractive index**

$$\frac{\partial^2 E}{\partial x \partial \omega} = \frac{q^2}{4\pi} \mu(\omega) \omega \left( 1 - \frac{1}{\beta^2 n^2(\omega)} \right)$$

Talk of Yaoguang Wang "Detector simulation status" 18/07/2022

JUNO-EU 24-25 October

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### 

### The modeling of the time rensonse affects more on the <u>1<sup>nd</sup></u> and the 2<sup>nd</sup> component



JUNO-EU 24-25 October

# Measurement of fluorescence time profile with the single photon counting technique

Time-correlated single photon counting (TCSPC) is a technique to measure the fluorescence decay time.

Under certain hypothesis ( $R_{sp} << R_{tr}$ ), the time of arrival of the photons w.r.t. to the trigger reproduces the fluorescence time distribution.

In our application, one PMT provides the START signal (trigger) and the other PMT gives the STOP signal.





### The exclusion of Cherenkov light on the fit mostly affects on the fast component



Tau1 relative error in function Cherenkov fraction

Monte-Carlo simulates different contribution of Cherenkov light

The fit does not consider the Cherenkov light

### Monte-Carlo study

# Systematic error due to the exclusion of the Cherenkov contribution in the fit — Cherenkov not included

### The exclusion of Cherenkov light on the fit mostly affects on the fast component



Tau1 relative error in function Cherenkov fraction

The part of the graph above 0.01 fraction makes no sense. In that case Cherenkov light becomes important and the fit doesn't work.

The relative error gets worse as the Cherenkov fraction increases

# Monte-Carlo study Systematic error due to the exclusion of the Cherenkov contribution in the fit —→Cherenkov not included

### The exclusion of Cherenkov light on the fit mostly affects on the fast component



### Monte Carlo study

## **Systematics studies: Cherenkov neglect**

Same Monte Carlo simulation of the sensitivity studies

Cherenkov simulated in the time distribution, but neglected in the fit

Relative error  $\tau$ 1 -0.05 -0.1 -0.15 -0.2 -0.25 0.02 0.002 0 004 0.006 0.008 0.0 0.016 0.018 0.0120.014 Cherenkov fraction

Tau1 relative error in function Cherenkov fraction

### Monte Carlo study

## **Systematics studies: Cherenkov neglect**

Same Monte Carlo simulation of the sensitivity studies

Cherenkov simulated in the time distribution, but neglected in the fit

Tau1 relative error in function Cherenkov fraction



The part of the graph above 0.01 fraction makes no sense. In that case Cherenkov light becomes important and the fit doesn't work.

The relative error gets worse as the Cherenkov fraction increases

### Monte-Carlo study Cherenkov sensitivity study



### Normalization of the fourth component



The fit model uses four components to describe the de-excitation time of the L.S.

These components are normalized to the integral of the exponential

For the fourth component this introduces an error

We improve the implementation of this normalization to consider this error

### Monte-Carlo study

### Systematic error introduced by fit — On 10<sup>5</sup> simulations

A simple Monte Carlo was realized to study the fit systematics.

The percentage uncertainty introduced by the fit is less than 5% on  $\tau_i$  and  $q_i$ .



### Monte-Carlo study

# Systematic error introduced by a different description of the detector response

Only 1 Gaussian was used instead of 3 to describe the system response

