

NEUTRINO OSCILLATION PHYSICS IN JUNO

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Joint Institute for Nuclear Research

EPS-HEP July 26, 2021





1 INTRODUCTION

- Neutrino mixing and oscillations
- Reactor $\overline{\nu}$ oscillations

2 JUNO AND TAO

- Detectors
- Status

3 OSCILLATION PHYSICS

- Reactor $\overline{\nu}_e$
- Solar ν_e from ⁸B
- Atmospheric $\nu_{\mu}/\overline{\nu}_{\mu}$
- Reactor $\overline{\nu}_s$

4 SUMMARY

Mixing Reactor $\overline{\nu}$

MANDATORY SLIDE I: NEUTRINO MIXING





Weak and mass eigenstates differ: $|\nu_{\alpha}\rangle = \sum U_{\alpha i}^{*}|\nu_{i}\rangle$ $\alpha - \text{flavor states}$ i - mass statesMixing parametrized by: • three mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$, • CP-violating phase: δ_{CP} .

 ν_3

 ν_2

 ν_1

 $\nu_e \square$

Mixing Reactor $\overline{\nu}$

MANDATORY SLIDE I: NEUTRINO MIXING



Weak and mass eigenstates differ: $|\nu_{\alpha}\rangle = \sum U_{\alpha i}^{*}|\nu_{i}\rangle$ α – flavor states i - mass statesMixing parametrized by: three mixing angles: $\theta_{12}, \theta_{23}, \theta_{13},$ • CP-violating phase: δ_{CP} . Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix:

 \checkmark $\theta_{23} \approx 45^{\circ}$ established through atmospheric and accelerator experiments: possibly maximal. ✓ $\theta_{12} \approx 34^{\circ}$ established through solar experiments and KamLAND: large, but not maximal. ✓ $\theta_{13} \approx 8^{\circ}$ established by reactor: Daya Bay, RENO, Double Chooz. NOvA and T2K • δ_{CP} unknown: ◆□▶ ◆□▶ ◆三▶ ◆三▶ ●目目 のへで



Mixing Reactor $\overline{\nu}$

MANDATORY SLIDE II: NEUTRINO MASS AND ORDERING





Mass splitting from oscillations

•
$$\Delta m^2_{21}~=(7.53\pm0.18) imes10^{-5}\,{
m eV}^2$$

•
$$\left|\Delta m^2_{32}\right| = (2.42 \pm 0.06) \times 10^{-3} \, {
m eV^2}$$

•
$$\left|\Delta m_{32}^2\right|/\Delta m_{21}^2\sim 32$$

Neutrino mass

• Mass limits, me	V:		
$m_2 > 0$			
$m_3 \neq 0$	oscillations		
$\sum m_{ u} \gtrsim$ 60			
$\sum m_ u \lesssim$ 120	cosmology	Planck [™]	
$m_{ u_e}{<}1100$	direct	KATRIN ^ℤ	
$\langle m_{etaeta} angle <~160$	0		
$m_{ m light}<~440$	0 u ho ho ho	GERDA-	<i>م</i> (~
Neutrino oscillations in JUNO		July 26, 2021	4, / 19

Mixing Reactor $\overline{\nu}$

MANDATORY SLIDE II: NEUTRINO MASS AND ORDERING





Mass splitting from oscillations

• $\Delta m_{21}^2 = (7.53 \pm 0.18) \times 10^{-5} \,\mathrm{eV}^2$

•
$$\left|\Delta m^2_{32}\right| = (2.42 \pm 0.06) \times 10^{-3} \, \mathrm{eV^2}$$

• $|\Delta m_{32}^2| / \Delta m_{21}^2 \sim 32$

Neutrino mass

• Mass limits. meV: 0 $m_2 >$ $m_3 \neq 0$ oscillations $\sum m_{\nu} \gtrsim 60$ Planck[™] $\sum m_{
u} \lesssim 120$ cosmology **KATRIN**[™] $m_{\nu_{e}} < 1100$ direct $\langle m_{\beta\beta} \rangle < 160$ GERDA[⊡] $0\nu\beta\beta$ $m_{\rm light} < 440$ July 26, 2021

Mixing Reactor $\overline{\nu}$

MANDATORY SLIDE II: NEUTRINO MASS AND ORDERING





Mass splitting from oscillations

- $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5} \, \mathrm{eV^2}$
- $\left|\Delta m_{32}^2\right| = (2.42 \pm 0.06) \times 10^{-3} \, \mathrm{eV}^2$
- $\left|\Delta m^2_{32}\right|/\Delta m^2_{21}\sim 32$
- Mass ordering: is ν_1 lighter than ν_3 ?

Neutrino mass

• Mass limits, meV: $m_2 > 0$ $m_3 \neq 0$ oscillations $\sum m_{\nu} \gtrsim 60$ $\sum m_{\nu} \lesssim 120$ cosmology Planck^{CP} $m_{\nu_e} < 1100$ direct KATRIN^{CP} $\langle m_{\beta\beta} \rangle < 160$ $m_{light} < 440$ $0\nu\beta\beta$ GERDA^{CP}







 $E_{
m vis} pprox E_{
u} - 0.78 \, {
m MeV}$

Maxim from JUNO (JINR)

Neutrino oscillations in JUNO

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Mixing Reactor $\overline{\nu}$



Mixing Reactor $\overline{\nu}$



Mixing Reactor $\overline{\nu}$



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July 26, 2021 555 / 19

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July 26, 2021 57 / 19

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July 26, 2021 58 / 19

Mixing Reactor $\overline{\nu}$



Challenges

- Unreliable antineutrino spectrum model:
- Energy resolution of the detector $\sigma < 3\%$ at 1 MeV:
- Energy scale of the detector (uncertainty < 1%):

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m vis} pprox E_{
u} - 0.78\,{
m MeV}$

- \hookrightarrow know reference spectrum
 - \hookrightarrow resolve the peaks
- \hookrightarrow ensure the peak positions

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Mixing Reactor $\overline{\nu}$



Challenges

- Unreliable antineutrino spectrum model:
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Mixing Reactor $\overline{\nu}$



Challenges

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 $E_{
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 \hookrightarrow know reference spectrum

 \hookrightarrow ensure the peak positions

 \hookrightarrow resolve the peaks



- Change of oscillation period with ordering \ll energy resolution
- Cumulative effect across the most energy range

 $E_{
m vis} pprox E_{
u} - 0.78\,{
m MeV}$

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Mixing Reactor $\overline{\nu}$

• Change of oscillation period with ordering \ll energy resolution

Introduction JUNO/TAO Oscillations Summary

- Cumulative effect across the most energy range
- Possible threat: fine structure in reactor $\overline{\nu}_e$ spectrum



 $E_{
m vis} pprox E_{
u} - 0.78\,
m MeV$

(plot: same Δm_{ee}^2)

PRL114

OSCILLATION PHYSICS WITH JUNO



- PMNS mixing matrix unitarity
- Mass splitting sum



Detectors Status

OSCILLATION PHYSICS WITH JUNO

Reactor $\overline{\nu}_e$ at	~53 km 😭	
• Parameters:	Neutrino Mass Ordering $\Delta m_{31}^2, \ \Delta m_{21}^2, \ \sin^2 2\theta_{12}$	(NMO)
Solar ν_e from	⁸ B	
• Rate:	17 $ u_e/{\sf day}$	
 Features: 	rate, day/night asymmetry	
• Parameters:	Δm_{21}^2 , $\sin^2 \theta_{12}$	



Maxim from JUNO (JINR)

Solar ⁸B [2006.11760], CPC45

OSCILLATION PHYSICS WITH JUNO

Reactor $\overline{\nu}_{e}$ at \sim 53 km Neutrino Mass Ordering (NMO) Parameters: Δm_{31}^2 , Δm_{21}^2 , $\sin^2 2\theta_{12}$ Solar ν_{e} from ⁸B O Δm_{21}^2 , $\sin^2 \theta_{12}$ Parameters: Reactor $\overline{\nu}_{e}$ at 30 m ٠. • Rate at TAO: 2000 $\overline{\nu}_e/day$ Features: spectrum shape Δm_{41}^2 , $\sin^2 2\theta_{14}$ Parameters:







OSCILLATION PHYSICS WITH JUNO



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- Neutrino Mass Ordering Δm_{31}^2 , Δm_{21}^2 , $\sin^2 2\theta_{12}$
- Solar ν_{e} from ⁸B ٢ Δm_{21}^2 , $\sin^2 \theta_{12}$
- Parameters:
- Reactor $\overline{\nu}_e$ at 30 m
- Δm_{41}^2 , sin² 2 θ_{14} Parameters:
- Atmospheric $\nu_{\mu}/\overline{\nu}_{\mu}$
- 200 kton-years:
- Features:
- Parameters:

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- 1233/1035 events
- angular distribution

NMO, $\sin^2 \theta_{23}$ Yellow Book (2015) [1507.05613], JPG43



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Detectors Status

OSCILLATION PHYSICS WITH JUNO





JUNO DETECTOR







JUNO DETECTOR

More light \rightarrow better resolution!

Target

- 20 kt LS
- Optimized LY
- Acrylic sphere





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July 26, 2021 72 / 19

JUNO DETECTOR

More light \rightarrow better resolution!

Target

- 20 kt LS
- Optimized LY
- Acrylic sphere



Support

• Stainless steel structure



LS — Liquid Scintillator LY — Light Yield

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JUNO DETECTOR

More light \rightarrow better resolution!

Target

- 20 kt LS
- Optimized LY
- Acrylic sphere



Support

• Stainless steel structure





- LS Liquid Scintillator
- LY Light Yield
- PMT PhotoMultiplier Tube
- QE Quantum Efficiency
- p.e. photo-electron

Light collection



- 18k 20" PMTs
- High QE: 29.6%
- 1350 p.e./MeV
- +26k 3" PMTs

JUNO DETECTOR

More light \rightarrow better resolution!

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Target

- 20 kt LS
- Optimized LY
- Acrylic sphere

Coils

• Compensation of the Earth Magnetic Field

Support

• Stainless steel structure





- LS Liquid Scintillator
- LY Light Yield
- PMT PhotoMultiplier Tube
- QE Quantum Efficiency
- p.e. photo-electron
- PS Plastic Scintillator

Light collection



- 18k 20" PMTs
- High QE: 29.6%
- 1350 p.e./MeV
- +26k 3" PMTs

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JUNO DETECTOR

More light \rightarrow better resolution!

Target

- 20 kt LS
- Optimized LY
- Acrylic sphere

Coils

• Compensation of the Earth Magnetic Field

Support

Stainless steel structure

lection Fignal/Backgrounds

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- LS Liquid Scintillator
- LY Light Yield
- PMT PhotoMultiplier Tube
- QE Quantum Efficiency
- p.e. photo-electron
- PS Plastic Scintillator

Muon veto

- Top Tracker: 3 layers PS
- Water pool

Light collection



- 18k 20" PMTs
- High QE: 29.6%
- 1350 p.e./MeV
- +26k 3" PMTs

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July 26, 2021 7₆ / 19

Detectors Status

JUNO AND TAO DETECTORS



	JUNO	
Attention	Energy resolution $\sigma \searrow$	
Method	Light collection $/$	
Scintillator	LS	
PMTs	18k 20"	
Coverage, % Light col. p.e./MeV σ_E at 1 MeV, %	+20k 3" 78 1200 1350 3	
Detectors Thermal power, GW Baseline IBD/day/AD	1 35.8 26.6 52 km 60 45	



Validity: June 2021

July 26, 2021 81 / 19

JUNO AND TAO DETECTORS



Plastic scintillator
Sealing Top shield
HOF E, neat instruction rayer
Filling port ACU
SS tank Cable
-50 °C
🖥 Side 🔰 🌈 Side 🛛
Shield // Shield
🙀 (HDPE) 🗟 🚺 Inner ball 📊 🛃 (HDPE)
Gd-LS
SIPM array -50 C
Cu shell
SS tank Support
PU, heat insulation layer
G10 HDPE, heat insulation layer G10
Lead and a second se
Ground I
i
1.7 m / 2.6 t GdLS

	ΤΑΟ	JUNO	
Attention	Energy resolution $\sigma \downarrow$		
Method	Light collection $/$ Dark noise \downarrow		
Scintillator	GdLS @ -50 °C	LS	
PMTs	SiPM	18k 20"	
	1.5M 5 mm	+26k 3"	
Coverage, %	94	78	
Light col. p.e./MeV	4500	$\frac{1200}{1350}$	
$\sigma_{\it E}$ at 1 MeV, %	2	3	
Detectors	1	1	
Thermal power, GW	4.6	35.8 26.6	
Baseline	30 m	52 km	
IBD/day/AD	2000	60 45	

July 26, 2021 822 / 19

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signal

Detectors Status

TAO — Taishan Antineutrino Observatory

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JUNO AND TAO LOCATION

• JUNO — Jiangmen Underground Neutrino Observatory





Thermal power, GW Total, GW

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JUNO AND TAO LOCATION

• JUNO — Jiangmen Underground Neutrino Observatory



TAO — Taishan Antineutrino Observatory



Total. GW

CIVIL CONSTRUCTION

✓ Civil construction: done.



Maxim from JUNO (JINR)

Neutrino oscillations in JUNO

July 26, 2021 10, / 19


Detectors Status

CIVIL CONSTRUCTION

- \checkmark Civil construction: done.
- ✓ Underground lab: done.
- ✓ Installation: soon.







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Neutrino oscillations in JUNO

July 26, 2021 102 / 19

Detectors Status

JUNO SCHEDULE





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Oscillation physics

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SENSITIVITY TO NEUTRINO MASS ORDERING



Yellow Book (2015) [1507.05613], JPG43 JUNO+IceCube [1911.06745], PRD101

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July 26, 2021 131 / 19

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SENSITIVITY TO NEUTRINO MASS ORDERING





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Yellow Book (2015) [1507.05613], JPG43

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JUNO+IceCube [1911.06745]. PRD101

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SENSITIVITY TO NEUTRINO MASS ORDERING





Changes since 2015

- ▼ Less favorable Δm_{32}^2
- ▼ No TS-3/4 cores less signal

Yellow Book (2015) [1507.05613], JPG43 JUNO+IceCube [1911.06745], PRD101

July 26, 2021

133 / 19

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SENSITIVITY TO NEUTRINO MASS ORDERING





Changes since 2015

- ▼ Less favorable Δm_{32}^2
- ▼ No TS-3/4 cores less signal
- ▲ Consider LS nonlinearity
- $\land \overline{\nu}_e$ spectrum by TAO

Yellow Book (2015) [1507.05613], JPG43 JUNO+IceCube [1911.06745], PRD101 > < @ > < ミト < ミト ミドニックへ ↔

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Changes since 2015 • Less favorable Δm_{32}^2

▲ Consider LS nonlinearity
 ▲ *v_e* spectrum by TAO

Higher LS light yield
 PMT optical model

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v Lower overburden 30% more μ

▼ No TS-3/4 cores

▲ PMT QE

SENSITIVITY TO NEUTRINO MASS ORDERING



 \hookrightarrow sensitivity boost due to tension for wrong ordering

Yellow Book (2015) [1507.05613], JPG43

JUNO+IceCube [1911.06745]. PRD101



less signal

27%→29%

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SENSITIVITY TO NEUTRINO MASS ORDERING



- Combined with accelerator or atmospheric experiment:
 - \hookrightarrow sensitivity boost due to tension for wrong ordering

 $> 5\sigma$





Changes since 2015 **v** Less favorable Δm_{32}^2 ▼ No TS-3/4 cores less signal ▲ Consider LS nonlinearity $\mathbf{A} \ \overline{\nu}_e$ spectrum by TAO **v** Lower overburden 30% more μ ▲ PMT QE 27%→29% ▲ Higher LS light vield PMT optical model ▲ No HZ cores ↓ background World reactors ↑ background

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SENSITIVITY TO NEUTRINO MASS ORDERING



Changes since 2015 **v** Less favorable Δm_{32}^2 ▼ No TS-3/4 cores less signal ▲ Consider LS nonlinearity $\mathbf{A} \ \overline{\nu}_{e}$ spectrum by TAO **v** Lower overburden 30% more μ ▲ PMT QE 27%→29% ▲ Higher LS light vield PMT optical model ▲ No HZ cores ↓ background World reactors ↑ background Dedicated publication in 2021 Yellow Book (2015) [1507.05613], JPG43 JUNO+IceCube [1911.06745]. PRD101



July 26, 2021 137 / 19

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JUNO AND NEUTRINO OSCILLATION PARAMETERS





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JUNO AND NEUTRINO OSCILLATION PARAMETERS

• JUNO will measure $\Delta m_{31}^2 / \Delta m_{32}^2$, Δm_{21}^2 and $\sin^2 2\theta_{12}$ with per-mille level precision.



July 26, 2021

142 / 19



JUNO AND NEUTRINO OSCILLATION PARAMETERS



• JUNO will measure $\Delta m_{31}^2 / \Delta m_{32}^2$, Δm_{21}^2 and $\sin^2 2\theta_{12}$ with per-mille level precision.





212

JUNO AND NEUTRINO OSCILLATION PARAMETERS



• JUNO will measure $\Delta m_{31}^2 / \Delta m_{32}^2$, Δm_{21}^2 and $\sin^2 2\theta_{12}$ with per-mille level precision.





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OSCILLATION PHYSICS WITH SOLAR ⁸B ν_{e}



Oscillations

• ⁸B ν_e are sensitive to the matter effect: Day/Night asymmetry



Neutrino oscillations in JUNO

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Oscillation physics with solar ⁸B ν_e



Oscillations

• $^8\mathrm{B}~
u_e$ are sensitive to the matter effect: Day/Night asymmetry

Detection

- Signal: ν_e elastic scattering off e^-
- Expected rate: 17 $\nu_e/{
 m day}$
- Limiting factors: LS purity, cosmic ray related background
- Baseline ${}^{238}\mathrm{U}/{}^{232}\mathrm{Th}$ contamination:

 $10^{-17} \, \text{g/g}$ P845: OSIRIS

► Extra Solar ⁸B [2006.11760], CPC45

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OSCILLATION PHYSICS WITH SOLAR ⁸B ν_e



Oscillations

• $^8\mathrm{B}~
u_e$ are sensitive to the matter effect: Day/Night asymmetry

Detection

- Signal: ν_e elastic scattering off e^-
- Expected rate: 17 $\nu_e/{
 m day}$
- Limiting factors: LS purity, cosmic ray related background
- Baseline ${}^{238}\mathrm{U}/{}^{232}\mathrm{Th}$ contamination: $10^{-17}\,\mathrm{g/g}$

Data and analysis

- Events binned vs zenith angle $\cos\theta_z$ and ν_e energy
- $\sim 20\%$ sensitivity to Δm^2_{21} and 8% sensitivity to $\sin^2 \theta_{12}$
- Rate constrained with SNO (NC)

Neutrino oscillations in JUNO

Solar ⁸B [2006.11760], CPC45

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OSCILLATION PHYSICS WITH ATMOSPHERIC $\nu_{\mu}/\overline{\nu}_{\mu}$



🕨 Extra

Atmospheric $u_{\mu}/
u_{e}$ spectra [2103.09908]

Oscillations

• Matter effect: θ_z dependence

Maxim from JUNO (JINR)

Neutrino oscillations in JUNO

July 26, 2021 161 / 19

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OSCILLATION PHYSICS WITH ATMOSPHERIC $\nu_{\mu}/\overline{\nu}_{\mu}$



Oscillations

• Matter effect: θ_z dependence

Detection

- Primary channel: $\nu_{\mu}/\overline{\nu}_{\mu}$ CC
- Expected statistics, 200 kton-years: 1233/1035 events
- Limiting factors: angular resolution / PID purity

Extra

July 26, 2021 162 / 19

Atmospheric ν_{μ}/ν_{e} spectra [2103.09908]

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Extra

Data and analysis

• Events binned vs zenith angle $\cos \theta_z$ (fine) and ν energy (coarse)

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- $\sim 1\sigma$ sensitivity to ordering in 10 years
- Potential: combination with reactor analysis



Atmospheric ν_{μ}/ν_{e} spectra [2103.09908]

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JUNO AND NEUTRINO OSCILLATION PARAMETERS



• JUNO will measure $\Delta m_{31}^2 / \Delta m_{32}^2$, Δm_{21}^2 and $\sin^2 2\theta_{12}$ with per-mille level precision.





 $\sin^2 \theta_{23}$ for sensitivity: to be estimated...

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Maxim from JUNO (JINR)

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July 26, 2021 17 / 19

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STERILE NEUTRINO SEARCH WITH TAO AND JUNO



Primary goal



• Reference reactor $\overline{\nu}_e$ spectrum with $\sigma = 2\%$ at 1 MeV.



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STERILE NEUTRINO SEARCH WITH TAO AND JUNO



Primary goal

• Reference reactor $\overline{\nu}_e$ spectrum with $\sigma = 2\%$ at 1 MeV.

Oscillations: reactor at 30 m

- Relevant range: $0.5\,{
 m eV}^2 \lesssim \Delta m_{41}^2 \lesssim 5\,{
 m eV}^2$
- $\bullet\ \sim$ large L counterbalanced with high energy resolution

July 26, 2021 182 / 19



TAO CDR [2005.08745]

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STERILE NEUTRINO SEARCH WITH TAO AND JUNO



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- Inverse beta decay with nGd tag
- Expected rate: 2000 $\overline{\nu}_e/{
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Detection

- Inverse beta decay with nGd tag
- Expected rate: 2000 $\overline{\nu}_e/{
 m day}$

Data and analysis

- Events, finely binned vs energy
- Simultaneous fit: TAO's 4 virtual subdetectors
- May verify Neutrino-4 best-fit: Δm^2_{41} =7.25 eV², sin² 2 θ_{14} =0.26



TAO CDR [2005.08745]

- Determination of the neutrino mass ordering:
 - 3σ in 6 years via reactor $\overline{\nu}_e$
 - $ightarrow 5\sigma$ when combined with accelerator or atmospheric experiments
 - $+1\sigma$ via atmospheric $u_{\mu}/\overline{
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 - 3σ in 6 years via reactor $\overline{\nu}_e$
 - ho > 5 σ when combined with accelerator or atmospheric experiments
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- Oscillation parameters measurement:
 - 3 oscillation parameters: θ_{12} , Δm_{21}^2 , Δm_{32}^2
 - Independent measurement of $heta_{12}$, Δm^2_{21} via solar neutrinos from 8B
 - θ_{23} measurement via atmospheric neutrinos



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- TAO:
 - $\blacktriangleright\,$ Precision reactor antineutrino spectrum with $\sigma_{\it E}\sim 2\%$ at 1 MeV
 - Sensitivity to sterile neutrino mixing

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- TAO:
 - Precision reactor antineutrino spectrum with $\sigma_E \sim 2\%$ at 1 MeV
 - Sensitivity to sterile neutrino mixing
- Broad physics program beyond oscillations: geo-, solar-, SN, DSNB neutrinos; proton decay.
- Expected to start data taking in 2022!



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Thank you for your attention!

Spare slides:



6 PMT STATUS

7 IBD SELECTION

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Spares Physics PMT IBD

Day/Night effect with solar ⁸B ν_e





Day/Night asymmetry



Maxim from JUNO (JINR)

July 26, 2021 21 / 19

Spares Physics PMT IBD

Atmospheric neutrino oscillations



Atmospheric ν_e spectrum E² Φ [GeV cm⁻² s⁻¹ sr¹ V, 10-3 HKKM14 ve Flux (w/o osc.) HKKM14 v. Flux (w/ osc.) 10-4 This work (5 yrs) v_e 1.8 Reco/MC 1.2 0 0.6 0.4 0.2 log₁₀ (E_v / GeV) -0.5 Maxim from JUNO (JINR)

NMO sensitivity vs time



 Atmospheric ν_{μ}/ν_{e} spectra [2103.09908]

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 July 26, 2021
 22 / 19

Neutrino oscillations in JUNO

JUNO PMT STATUS



Large 20" PMT system

- 12'768 MCP PMTs by NNVT: delivered.
- 5'000 Dynode PMTs by Hamamatsu: delivered.
- Testing: mostly done.
- Protection cover: production started.

NNVT MCP



Hamamatsu Dynode





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Small 3" PMT system

- ✓ Complementary PMT system:
 - Increase dynamic range.
 Control systematics.
- 26'000 PMTs by HZC: produced.

NNVT MCP



Hamamatsu Dynode





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	NNVT	Hamamatsu	HZC
PDE, %	28.3	28.1	24
TTS, ns	12	2.7	1.5

NNVT MCP



Hamamatsu Dynode





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INVERSE BETA DECAY (IBD) AND SELECTION CRITERIA





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July 26, 2021 241 / 19

INVERSE BETA DECAY (IBD) AND SELECTION CRITERIA





Neutrino oscillations in JUNO

July 26, 2021 24₂ / 19

INVERSE BETA DECAY (IBD) AND SELECTION CRITERIA





Maxim from JUNO (JINR)

Neutrino oscillations in JUNO

July 26, 2021 243 / 19

INVERSE BETA DECAY (IBD) AND SELECTION CRITERIA



INVERSE BETA DECAY (IBD) AND SELECTION CRITERIA



INVERSE BETA DECAY (IBD) AND SELECTION CRITERIA



Yellow Book (2015) [1507.05613], JPG43



					JUNO S/N	Unc.
Neutrino backgro	ound sources	_	• IBD	events/AD	45	
 Nearby reactors w World reactors Geo-<i>v</i>_e 	vith <i>L</i> ≠ 53 km: Daya Bay, Ling Ao	_	Geo v Accidentals ${}^{8}\text{He}/{}^{9}\text{Li}$ Fast neutrons ${}^{13}\text{C}(\alpha, n)^{16}\text{O}$	% % % %	2.4 2.0 3.6 0.3 0.1	30 negligible 20 100 50
		_	 Total bkg 	%	8.6	
Accidentals	β - n isotopes	Fast	neutrons	$^{13}\mathrm{C}(lpha, \mathbf{\textit{n}})^{16}$	³ O	ACU
Maxim from JUNO	(JINR)	Neutrino	oscillations in JUNO		Ju	v 26, 2021 25, / 19

Yellow Book (2015) [1507.05613], JPG43



					JUNO S/N	Unc.
Neutrino backgro	ound sources	•	IBD	events/AD	45	
 Nearby reactors v World reactors Geo-<i>v</i>_e 	vith <i>L</i> ≠ 53 km: Daya Bay, Ling Ao	•	Geo v Accidentals ${}^{8}\mathrm{He}/{}^{9}\mathrm{Li}$ Fast neutrons ${}^{13}\mathrm{C}(\alpha, \textbf{\textit{n}}){}^{16}\mathrm{O}$	% % % %	2.4 2.0 3.6 0.3 0.1	30 negligible 20 100 50
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Accidentals	β - n isotopes	Fast	neutrons	$^{13}\mathrm{C}(lpha, \textit{n})^{16}$	O	ACU
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Maxim from JUNO	(JINR)	Neutrino os	cillations in JUNO		Jul	v 26, 2021 25 ₂ / 19

Yellow Book (2015) [1507.05613], JPG43



					JUNO S/N	Unc.
Neutrino backgro	ound sources	•	IBD	events/AD	45	
 Nearby reactors v World reactors Geo-ve 	vith <i>L</i> ≠ 53 km: Daya Bay, Ling Ao	•	Geo $ u $ Accidentals ${}^{8}\mathrm{He}/{}^{9}\mathrm{Li}$ Fast neutrons ${}^{13}\mathrm{C}(lpha, n){}^{16}\mathrm{O}$	% % % %	2.4 2.0 3.6 0.3 0.1	30 negligible 20 100 50
		•	Total bkg	%	8.6	
Accidentals	β - n isotopes	Fast	neutrons	$^{13}\mathrm{C}(lpha, \textit{n})^{16}$	0	ACU
$\gamma \int \beta, \gamma$						≣⊧≣≣ ৩৭০
Maxim from JUNO	(JINR)	Neutrino os	cillations in JUNO		Jul	v 26, 2021 25, / 1

Yellow Book (2015) [1507.05613], JPG43



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Neutrino backgro	und sources	•	IBD	events/AD	45	
 Nearby reactors w World reactors Geo-ve 	ith <i>L</i> ≠ 53 km: Daya Bay, Ling Ao	• • •	Geo v Accidentals ${}^{8}\text{He}/{}^{9}\text{Li}$ Fast neutrons ${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$ Total bkg	% % % %	2.4 2.0 3.6 0.3 0.1 8.6	30 negligible 20 100 50
Accidentals	β - <i>n</i> isotopes	Fast n	eutrons	$^{13}\mathrm{C}(lpha, \textit{n})^{16}$	0	ACU
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Maxim from JUNO (.	JINR)	Neutrino oscil	lations in JUNO		Jul	y 26, 2021 25 ₄ / 1

Yellow Book (2015) [1507.05613], JPG43



					JUNO S/N	Unc.	
Neutrino backgro	ound sources	•	IBD	events/AD	45		•
 Nearby reactors w World reactors Geo-ve 	vith <i>L</i> ≠ 53 km: Daya Bay, Ling Ao	• • •	Geo v Accidentals ${}^{8}\mathrm{He}/{}^{9}\mathrm{Li}$ Fast neutrons ${}^{13}\mathrm{C}(\alpha, n){}^{16}\mathrm{O}$ Total bkg	% % % % %	2.4 2.0 3.6 0.3 0.1 8.6	30 negligible 20 100 50	-
Accidentals	β - <i>n</i> isotopes ${}^{8}\mathrm{He}/{}^{9}\mathrm{Li}/\mu$	Fast n	eutrons	$^{13}\mathrm{C}(\alpha, \mathbf{n})^{16}\mathrm{C}$		ACU	>
$\gamma \int \beta, \gamma$			>			≣া হা হা হা হা	10
Maxim from JUNO (JINR)	Neutrino oscil	lations in JUNO		Jul	y 26, 2021 25 ₅ /	19

Yellow Book (2015) [1507.05613], JPG43



					JUNO S/N	Unc.
Neutrino backgro	und sources	•	IBD	events/AD	45	
 Nearby reactors w World reactors Geo-ve 	rith <i>L</i> ≠ 53 km: Daya Bay, Ling Ao	• • •	Geo v Accidentals ${}^{8}\mathrm{He}/{}^{9}\mathrm{Li}$ Fast neutrons ${}^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ Total bkg	% % % %	2.4 2.0 3.6 0.3 0.1 8.6	30 negligible 20 100 50
Accidentals	β - <i>n</i> isotopes $^{8}\mathrm{He}/^{9}\mathrm{Li}$, μ	Fast n	eutrons	$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{C}(\alpha, n)^{16$)	ACU
$\overbrace{\gamma}_{\beta,\gamma}$				• • • •		
Maxim from JUNO (JINR)	Neutrino oscil	lations in JUNO		Jul	y 26, 2021 25 ₆ / 19

Yellow Book (2015) [1507.05613], JPG43



					JUNO S/N	Unc.	
Neutrino backgro	ound sources	•	IBD	events/AD	45		_
 Nearby reactors w World reactors Geo-\$\overline{\nu}_e\$ 	with <i>L</i> ≠ 53 km: Daya Bay, Ling Ao	•	Geo v Accidentals ${}^{8}\mathrm{He}/{}^{9}\mathrm{Li}$ Fast neutrons ${}^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ Total bkg	% % % %	2.4 2.0 3.6 0.3 0.1 8.6	30 negligible 20 100 50	
Accidentals γ	β - <i>n</i> isotopes ⁸ He/ ⁹ Li μ	Fast n	eutrons	$\overset{^{13}\mathrm{C}(\alpha,\textit{n})^{16}\mathrm{C}}{}$		ACU	\wedge
Maxim from IUNO	(IINR)	Neutrino oscil	lations in IUNO			■トヨー ション v 26 2021 25	<u>ک</u> ۹ ۲
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Yellow Book (2015) [1507.05613], JPG43



					JUNO S/N	Unc.	
Neutrino backgro	ound sources	•	IBD	events/AD	45		-
 Nearby reactors w World reactors Geo-<i>v</i>_e 	/ith <i>L</i> ≠ 53 km: Daya Bay, Ling Ao	•	Geo v Accidentals ${}^{8}\mathrm{He}/{}^{9}\mathrm{Li}$ Fast neutrons ${}^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ Total bkg	% % % %	2.4 2.0 3.6 0.3 0.1 8.6	30 negligible 20 100 50	_
Accidentals	β - <i>n</i> isotopes ⁸ He/ ⁹ Li μ	Fast n	eutrons	$^{13}C(\alpha, n)^{16}C$		ACU	\wedge
γ β, γ	nGd			<	· · · · · · · · · · · · · · · · · · ·		1
Maxim from JUNO (JINR)	Neutrino oscil	lations in JUNO		Jul	y 26, 2021 25 ₈	/ 19

Yellow Book (2015) [1507.05613], JPG43



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Neutrino backgro	ound sources	•	IBD	events/AD	45	
 Nearby reactors w World reactors Geo-ve 	/ith <i>L</i> ≠ 53 km: Daya Bay, Ling Ao	•	Geo v Accidentals ${}^{8}\mathrm{He}/{}^{9}\mathrm{Li}$ Fast neutrons ${}^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ Total bkg	% % % %	2.4 2.0 3.6 0.3 0.1 8.6	30 negligible 20 100 50
Accidentals γ β , γ	β - <i>n</i> isotopes ⁸ He/ ⁹ Li μ <i>n</i> Gd	Fast n	eutrons	$^{13}\mathrm{C}(\alpha, n)^{16}$		ACU
Maxim from JUNO (JINR)	Neutrino oscil	lations in JUNO		Jul	y 26, 2021 25 ₉ / 19

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Neutrino backgro	und sources	•	IBD	events/AD	45	
 Nearby reactors w World reactors Geo-ve 	ith <i>L</i> ≠ 53 km: Daya Bay, Ling Ao	•	Geo v Accidentals ${}^{8}\text{He}/{}^{9}\text{Li}$ Fast neutrons ${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$	% % % %	2.4 2.0 3.6 0.3 0.1 8.6	30 negligible 20 100 50
Accidentals γ β, γ	β - <i>n</i> isotopes ⁸ He/ ⁹ Li μ <i>n</i> Gd	Fast r	neutrons	70 $^{13}C(\alpha, n)^{16}C$		ACU
Maxim from JUNO (.	JINR)	Neutrino osci	llations in JUNO		July	26, 2021 2510 / 19

Yellow Book (2015) [1507.05613], JPG43



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Neutrino backgro	und sources	•	IBD	events/AD	45	
 Nearby reactors w World reactors Geo-<i>v</i>_e 	ith <i>L</i> ≠ 53 km: Daya Bay, Ling Ao	•	Geo v Accidentals ⁸ He/ ⁹ Li Fast neutrons ¹³ C(α , n) ¹⁶ O	% % % %	2.4 2.0 3.6 0.3 0.1 8.6	30 negligible 20 100 50
Accidentals	β - <i>n</i> isotopes ⁸ He/ ⁹ Li , μ β <i>n</i> Gd	Fast n	neutrons	$^{13}C(\alpha, n)^{16}C$		ACU
Maxim from JUNO (.	JINR)	Neutrino osci	llations in JUNO		July	26, 2021 25 ₁₁ / 19

Yellow Book (2015) [1507.05613], JPG43



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Neutrino backgro	und sources	•	IBD	events/AD	45	
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Yellow Book (2015) [1507.05613], JPG43



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Neutrino background sources		•	IBD	events/AD	45	
 Nearby reactors w World reactors Geo-ve 	/ith <i>L</i> ≠ 53 km: Daya Bay, Ling Ao	•	Geo v Accidentals ${}^{8}\mathrm{He}/{}^{9}\mathrm{Li}$ Fast neutrons ${}^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ Total bkg	% % % % %	2.4 2.0 3.6 0.3 0.1 8.6	30 negligible 20 100 50
Accidentals γ β, γ	β - <i>n</i> isotopes ⁸ He/ ⁹ Li μ <i>n</i> Gd	Fast n	eutrons	$^{13}C(\alpha, n)^{16}$		ACU
Maxim from JUNO (JINR)	Neutrino oscil	lations in JUNO		July	26, 2021 2513 / 19

Yellow Book (2015) [1507.05613], JPG43



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 Nearby reactors w World reactors Geo-ve 	rith <i>L</i> ≠ 53 km: Daya Bay, Ling Ao	• • •	Geo v Accidentals ${}^{8}\text{He}/{}^{9}\text{Li}$ Fast neutrons ${}^{13}\text{C}(\alpha, n)^{16}\text{O}$ Total bkg	% % % % %	2.4 2.0 3.6 0.3 0.1 8.6	30 negligible 20 100 50
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Maxim from JUNO (JINR)	Neutrino osci	llations in JUNO		July	26, 2021 25 ₁₄ / 19

Yellow Book (2015) [1507.05613], JPG43



				J	UNO S/N	Unc.
Neutrino backgro	ound sources	•	IBD	events/AD	45	
 Nearby reactors w World reactors Geo-<i>v</i>_e 	<i>i</i> ith <i>L ≠</i> 53 km: Daya Bay, Ling Ao	•	Geo v Accidentals ${}^{8}\text{He}/{}^{9}\text{Li}$ Fast neutrons ${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$	% % % %	2.4 2.0 3.6 0.3 0.1	30 negligible 20 100 50
Accidentals γ	β - <i>n</i> isotopes ⁸ He/ ⁹ Li μ <i>n</i> Gd	Fast nGd	heutrons	$^{13}C(\alpha, n)^{16}O$		ACU
Maxim from JUNO	JINR)	Neutrino osc	illations in JUNO		July	26, 2021 2515 / 19

Yellow Book (2015) [1507.05613], JPG43



				-	JUNO S/N	Unc.
Neutrino background sources		•	IBD	events/AD	45	
 Nearby reactors v World reactors Geo-<i>v</i>_e 	vith <i>L ≠</i> 53 km: Daya Bay, Ling Ao	•	Geo v Accidentals ${}^{8}\text{He}/{}^{9}\text{Li}$ Fast neutrons ${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$	% % % %	2.4 2.0 3.6 0.3 0.1	30 negligible 20 100 50
Accidentals γ	β-n isotopes ⁸ He/ ⁹ Li μ β nGd	Fast n nGd	heutrons	$^{13}C(\alpha, n)^{16}C$		
Maxim from JUNO	(JINR)	Neutrino osc	illations in JUNO		July	26, 2021 25 ₁₆ / 19

Yellow Book (2015) [1507.05613], JPG43



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Neutrino background sources		•	IBD	events/AD	45	
 Nearby reactors w World reactors Geo-<i>v</i>_e 	ith <i>L</i> ≠ 53 km: Daya Bay, Ling Ao	•	Geo v Accidentals ${}^{8}\text{He}/{}^{9}\text{Li}$ Fast neutrons ${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$	% % % % %	2.4 2.0 3.6 0.3 0.1	30 negligible 20 100 50
Accidentals	β - <i>n</i> isotopes ⁸ He/ ⁹ Li μ <i>n</i> Gd	Fast r	Fotal bkg neutrons	n Gd	$\begin{array}{c} 8.6 \\ 0 \\ \hline \\ C \\ \hline \\ \end{array} \right) \left(\begin{array}{c} AmG \\ \hline \\ \gamma \\ \hline \\ \hline \\ \end{array} \right) \left(\begin{array}{c} amG \\ \hline \\ \hline \\ \end{array} \right) \left(\begin{array}{c} amG \\ \hline \\ \hline \\ \hline \\ \end{array} \right) \left(\begin{array}{c} amG \\ \hline \\ $	ACU
Maxim from JUNO (.	JINR)	Neutrino osci	llations in JUNO		July	26, 2021 25 ₁₇ / 19

Yellow Book (2015) [1507.05613], JPG43



					JUNO S/N	Unc.
Neutrino background sources		•	IBD	events/AD	45	
 Nearby reactors w World reactors Geo-<i>v</i>_e 	ith <i>L</i> ≠ 53 km: Daya Bay, Ling Ao	•	Geo v Accidentals ${}^{8}\text{He}/{}^{9}\text{Li}$ Fast neutrons ${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$	% % % %	2.4 2.0 3.6 0.3 0.1	30 negligible 20 100 50
		•	Total bkg	%	8.6	
Accidentals	β - <i>n</i> isotopes ${}^{^{8}\mathrm{He}/^{9}\mathrm{Li}}$, μ	Fast	neutrons μ	$^{13}\mathrm{C}(lpha, \mathbf{n})^{16}$	O AmG	ACU
$\begin{array}{c} \gamma \\ & \uparrow \\ & \uparrow \\ & \beta, \gamma \end{array}$	B nGd	nGo	p	nGd · · · · · · · · · · · · · · · · · · ·	C γ	الله الله الله الله الله الله الله الل
Maxim from JUNO (.	JINR)	Neutrino oso	illations in JUNO		July	v 26, 2021 25 ₁₈ / 1

Yellow Book (2015) [1507.05613], JPG43



					JUNO S/N	Unc.
Neutrino background sources		•	IBD	events/AD	45	
 Nearby reactors w World reactors Geo-ve 	vith <i>L</i> ≠ 53 km: Daya Bay, Ling Ao	•	Geo $ u $ Accidentals ${}^{8}\mathrm{He}/{}^{9}\mathrm{Li}$ Fast neutrons ${}^{13}\mathrm{C}(\alpha, \textit{n}){}^{16}\mathrm{O}$	% % % %	2.4 2.0 3.6 0.3 0.1	30 negligible 20 100 50
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Accidentals	β - <i>n</i> isotopes ${}^{^{8}\mathrm{He}/^{9}\mathrm{Li}}$, μ	Fast	neutrons μ	$^{13}\mathrm{C}(lpha, \mathbf{n})^{16}$	O	ACU
$\begin{array}{c} \gamma \\ \beta, \gamma \\ \end{array}$	β nGd	nGc	p	nGd • • • • • • • • • • • • • • • • • • •		
Maxim from JUNO (JINR)	Neutrino oso	illations in JUNO		July	26, 2021 25 ₁₉ / 1