Strategy for Measureing the Radioactive Contamination of Liquid Scintillator with the Pre-detector of JUNO: OSIRIS

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1. JUNO & OSIRIS Detector

- **JUNO**
  - 700 m depth underground, 55 km from 6 nuclear cores
  - 20k tons of liquid scintillator (LS), contained inside an acrylic sphere with radius of 17.4 m
  - 18k 20-inch PMTs + 20k 3-inch PMTs
  - Detect antineutrinos via **inverse beta decay (IBD)**
  - Main goal: determine neutrino mass ordering and neutrino oscillation parameters

Current Status: under construction

- Installing the lower acrylic hemisphere

Fig1. An onsite view of JUNO central detector in construction

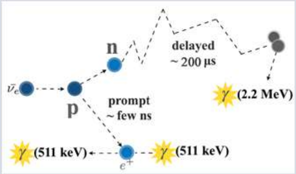


Fig2. Inverse beta decay (IBD) and neutron capture in LS

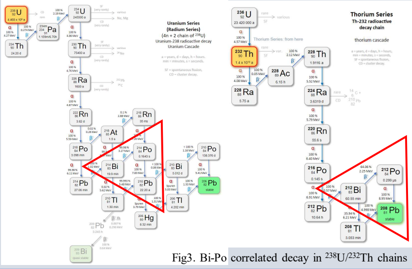


Fig3. Bi-Po correlated decay in $^{238}U/^{232}Th$ chains

- **OSIRIS** **(Online Scintillator Internal Radioactivity Investigation System)**
  - 19.6 tons of LS in a cylindrical acrylic vessel (AV) of 19.6 m^3
  - 64+12 microchannel plate 20-inch PMTs
  - Main goal: measure radioactivity (mainly ^{238}U, ^{232}Th, ^{14}C, and ^{85}Kr) contamination level of LS before transfering to JUNO CD

Current Status: Enter the 1st full LS phase and start physics data taking this spring

- Water filled both inside and outside AV
- Replace water by LS in AV from top

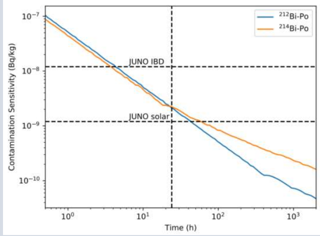


Fig4. Sensitivity of OSIRIS to $^{238}U/^{232}Th$ as a function of measurement time for ^{214}Bi-^{214}Po/ ^{212}Bi-^{212}Po in equilibrium, estimation based on Monte-Carlo simulation[1]

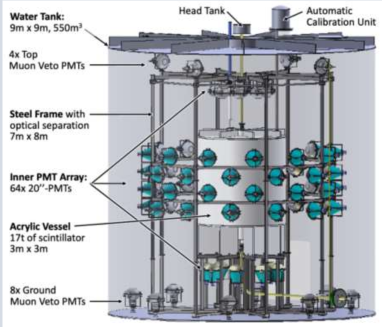


Fig5. A view of inside integration of OSIRIS detector

2. Measurement on $^{238}U/^{232}Th$ in LS

Strategy

- Measure time-correlated prompt-delayed signals in $^{238}U/^{232}Th$ decay chains

Radioactive Isotope	Correlated decay	Prompt Signal				Delayed Signal			
		Decay type	Life time	Energy [MeV]	Branch ratio	Decay type	Life time	Energy [MeV]*	Branch ratio
^{238}U	^{214}Bi-^{214}Po	β^-	28.7 min	**3.27**	99.98%	α	**237 us**	7.83	100%
^{232}Th	^{212}Bi-^{212}Po	β^-	87.4 min	**2.25**	64.06%	α	**431 ns**	8.95	100%

*α visible energy is around 1/10 of its true energy due to quenching

- Background: accidental coincidence, cosmogenic isotopes, etc.

Selection

- Energy cuts based on data
- dt cut limited by firmware performance
- Branch ratio is included in total efficiency

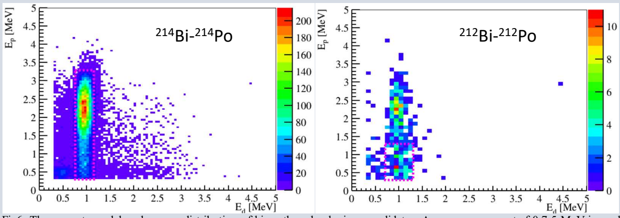


Fig6. The prompt v.s. delayed energy distribution of bismuth and polonium candidates. A coarse energy cut of 0.7-5 MeV is used for all events with different dt cuts and multiplicity vetos for ^{214}Bi-^{214}Po and ^{212}Bi-^{212}Po respectively.

Selection Cut	Prompt Energy	Delayed Energy	Prompt-delay dt	Multiplicity Veto	Muon Veto	Total efficiency
^{214}Bi-^{214}Po	0.3-3.3 MeV	0.3-1.3 MeV	1-1500 us	no event > 0.3 MeV in 1500 us/ns before (after) prompt (delayed) signals	(0, 500) us after all muons	94.21%
^{212}Bi-^{212}Po	0.75-1.15 MeV	0.7-1.3 MeV	900-1500 ns			5.99%

Results

- Data acquired for ~291 hours
- ^{214}Bi-^{214}Po: **30370** candidates selected
- ^{212}Bi-^{212}Po: **129** candidates selected

- dt distributions are consistent with $^{214/212}Po$ life time
- Inefficiency below 900 ns in dt distribution of ^{212}Bi-^{212}Po is caused by a deadtime issue of firmware

- Efficiency corrected for data points in ^{214}Bi-^{214}Po rate evolution plot
- Rn^{222} leakage observed, verified due to LS circulation
- Equilibrium part of ^{214}Bi-^{214}Po (from ^{238}U chain) is highly correlated with other parameters in fitting until the plateau is reached
- ^{212}Bi-^{212}Po is lack of statistics to produce a rate evolution plot

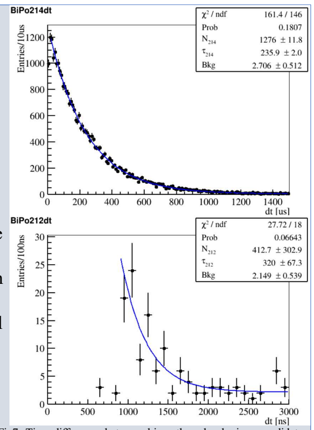


Fig7. Time difference between bismuth and polonium candidates

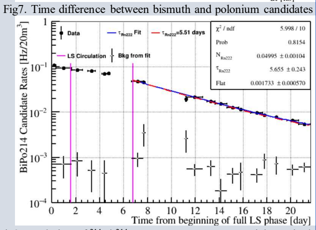


Fig8. Evolution of ^{214}Bi-^{214}Po rate. Dots are exponential part in dt distribution of data taken each day while crosses are backgrounds

Outlook

- JUNO LS is expected to reach a contamination level of 10^{-15} – 10^{-17} g/g for reactor neutrino and solar neutrino studies[2]
- The expectation translates into **0.1-10.7** uBq/m^3 of ^{214}Bi-^{214}Po in ^{238}U chain and **0.04-3.50** uBq/m^3 of ^{212}Bi-^{212}Po in ^{232}Th chain
- Firmware will be updated in the nearby future
- More data and further study is in progress to obtain the $^{238}U/^{232}Th$ contamination level

3. Singles Analysis

- Energy spectrum obtained in unit of photon electron (p.e.) charge, calibrated to s.p.e. peak
- Contributions from different radioactive isotopes observed
- Monte Carlo simulation under way for spectral fit

- New vertex reconstruction method based on hitting map is deployed
- High-counting spot in x-y plane is near to the wall, probably contributed by radioactivity in the rock
- Calibration data and further investigation is ongoing to understand the spot

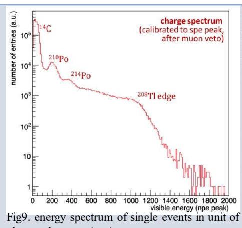


Fig9. energy spectrum of single events in unit of photon electrons (p.e.)

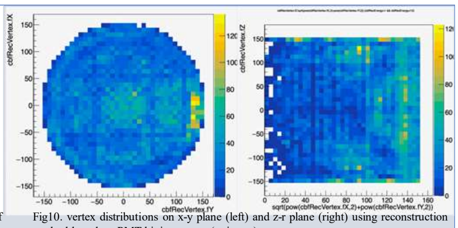
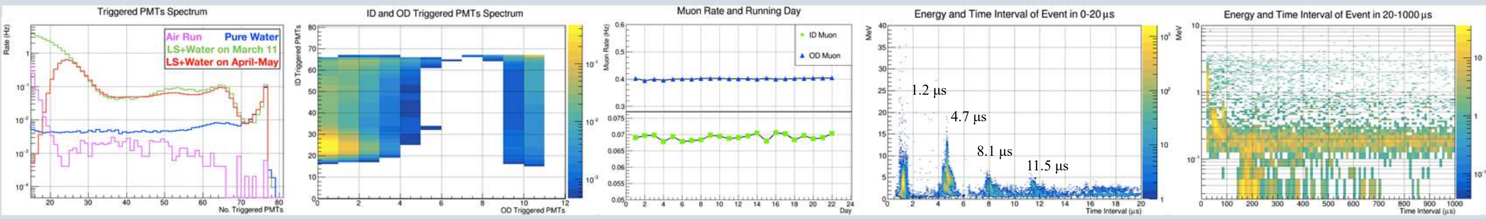


Fig10. vertex distributions on x-y plane (left) and z-r plane (right) using reconstruction method based on PMT hitting maps. (unit: cm)

4. Muon Analysis

- Event rate and No. triggered PMTs, corresponding to different detector filling phase: air run, pure water, liquid scintillator (LS)+water phase
- Muon criteria: Total event energy of inner detector: 20 MeV *(1 MeV = 390 p.e.)*
  Triggered PMTs of outer detector: 8 out of 12 PMTs

- Analyzed 22 days of running day: Muon rate, ~0.07 Hz for inner detector and ~0.4 Hz for outer detector
- The muon correlated event when determined muon from both inner and outer detector
  - Determing the after muon event with different time window: 20 and 1000 µs
- First 20 µs event after muon: found the afterpulse signals, follows the mother muon event



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Reference

[1] A. Abusleme et al. Eur.Phys.J.C 81 (2021) 11, 973

[2] A. Abusleme et al. Prog.Part.Nucl.Phys. 123 (2022) 103927