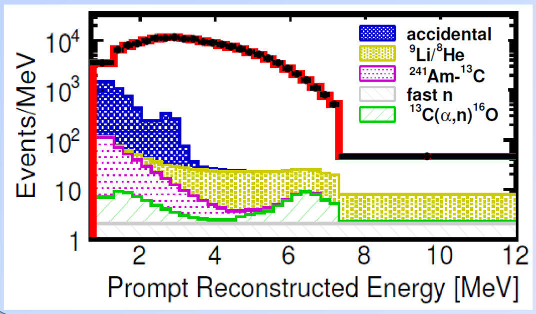
Natural radioactivity and $^{13}C(\alpha,n)^{16}O$ background of the Daya Bay Reactor Neutrino Experiment

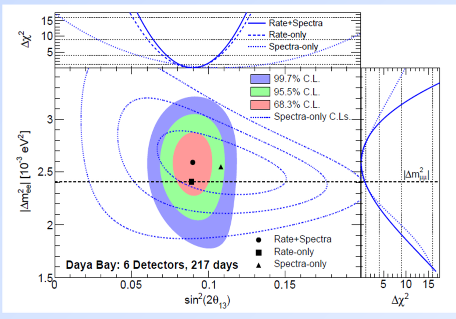
Introduction

The Daya Bay experiment is designed to precisely measure the neutrino oscillation angle θ_{13}.

With 217 days data, an improved measurement of $\sin^2 2\theta_{13}$=0.090+0.008-0.009 and $|\Delta M^2_{ee}|$ = (2.59+0.19-0.20)×10^{-3}eV^2 is obtained using anti-neutrino rate and spectra information.

The poster discusses natural radioactivity in the Daya Bay low background detector and related $^{13}C(\alpha,n)^{16}O$ background.

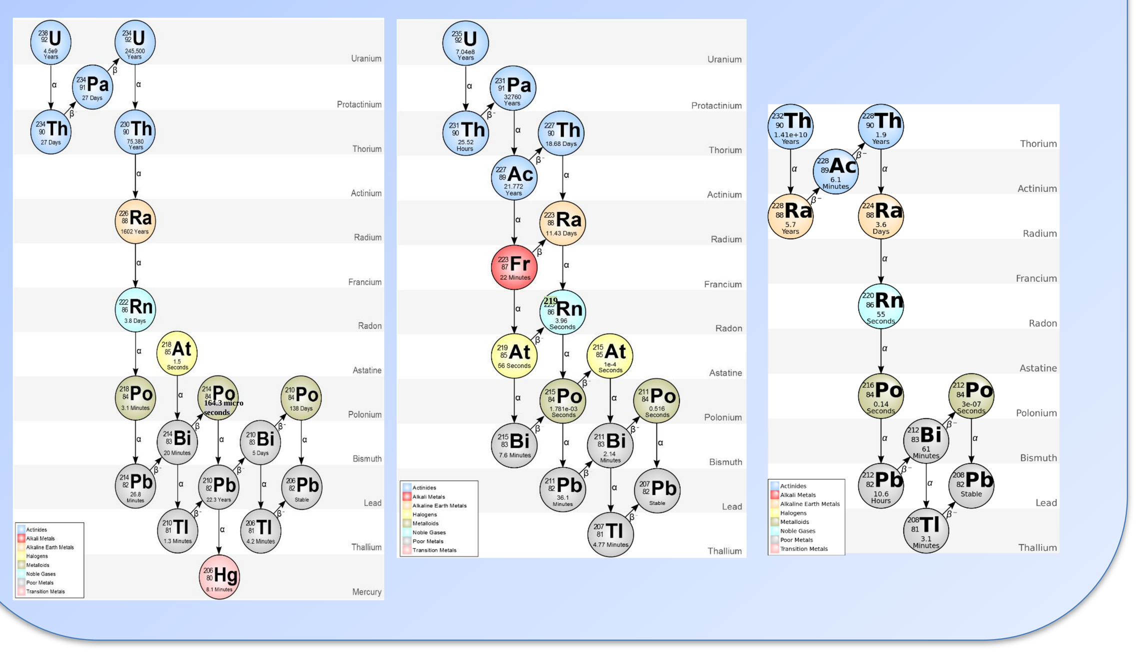




Natural radioactivity

Natural radioactivity are well known as three long life decay chains: ^{238}U, ^{232}Th and ^{235}U, and one long life isotopes ^{40}K.

Three decay chains containing α decays are to be studied.



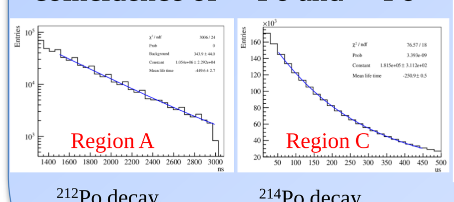
Cascade decays

Cascade decays are utilized to study decay chain rates.

(1) ^{238}U chain: ^{214}Bi --- ^{214}Po (164.3μs) --- ^{210}Po

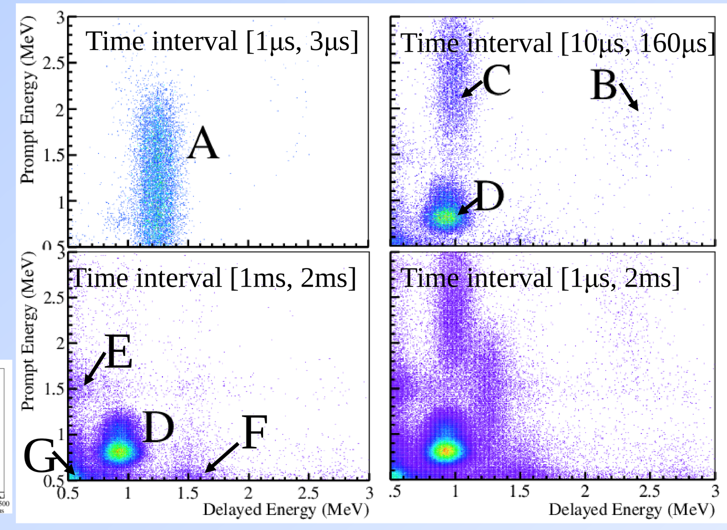
(2) ^{232}Th chain: ^{212}Bi --- ^{212}Po (300ns) --- ^{208}Po

Region A: cascade decay 2
Region B: hydrogen captured anti-neutrino events
Region C: cascade decay 1
Region D: **^{227}Ac decay chain**
Region E, F: accidental coincidence of ^{210}Po and ^{40}K
Region G: accidental coincidence of ^{210}Po and ^{210}Po



^{212}Po decay, measured half life 311ns

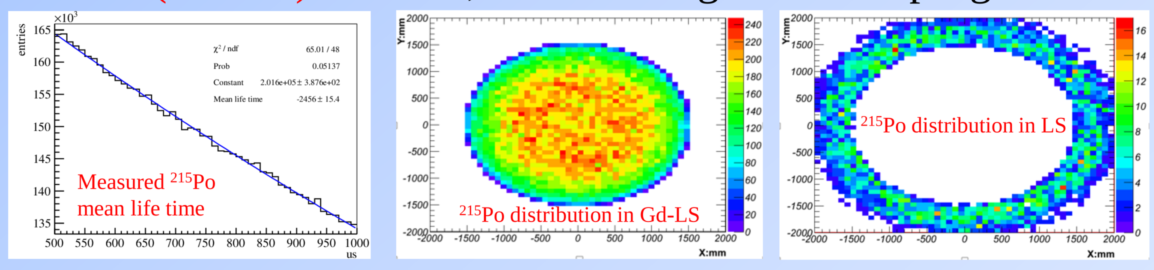
^{214}Po decay, measured half life 173.8 μs



Fully understood time coincident events at low energies (E<3MeV)

Discussion of ^{227}Ac

^{227}Ac is the daughter nuclei of ^{235}U, with a half life time 21.77 years. There is also a cascade decay in ^{227}Ac chain: ^{219}Rn --- ^{215}Po (1.78ms) --- ^{211}Pb, which is Region D in top right slide.



Measured half life time is 1.70ms, consistent with prediction.

The cascade decay mainly exists in Gd doped liquid scintillator, indicating it is induced by the mixing of Gd to the liquid scintillator.

There are two steps to mix Gd into LS:

1) Purification of $GdCl_3$ samples,
2) Complexation of Gd and TMHA (3,5,5-trimethylhexanoic acid)

Step 1 mainly removes U, Th, Pa, and step 2 mainly removes Ra.

^{238}U and ^{232}Th chains are removed efficiently by hundred times.

^{227}Ac in ^{235}U chain are NOT removed at all (first observation).

Rates of decay chains

Rates of decay chains are determined with two methods:

1) Use tight selection cuts, correct for the efficiency.
2) Use loose selection cuts, subtract accidental backgrounds

Results of the two methods are well consistent.

Assumption: the decay chain is under equilibrium.

	^{238}U	^{232}Th	^{227}Ac
Bq/g	4.5×10^{-10}	9.5×e^{-9}	1.0×e^{-8}

Ratio of ^{227}Ac and ^{238}U rates can be utilized to estimate purification effects:

1) Assume ^{227}Ac and ^{238}U chains are under equilibrium
2) Assume ^{227}Ac are not removed in the purification

The mass fraction of ^{238}U and ^{235}U in the natural is 0.993 and 0.007, converting to decay rates the ratio is 21.5:1.

The measured ratio is 0.045:1.

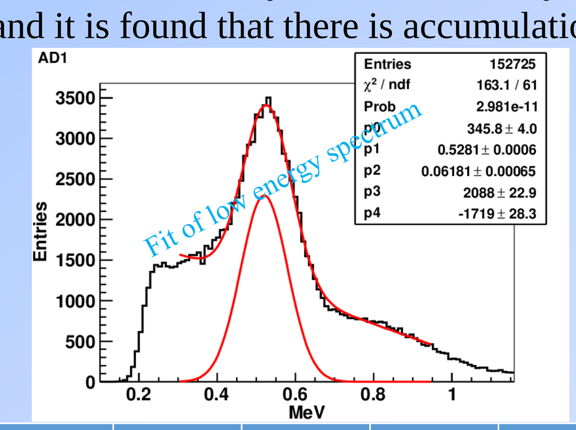
Based on the above assumptions, $GdCl_3$ purification removes ^{238}U by about 480 times.

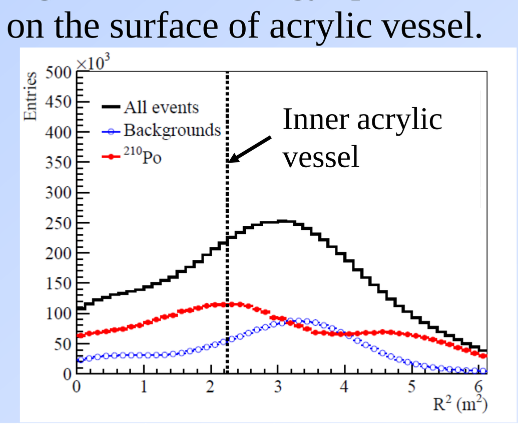
^{210}Pb (half life 22.3 years) study

^{210}Pb is the daughter of ^{222}Rn (half life 3.8 days, about 50Bq/m^3 in the air).

Via two β decays, ^{210}Pb decays to ^{210}Po, which is a 5.3MeV α emitter, and an important $^{13}C(\alpha,n)^{16}O$ background source.

Rate of ^{210}Po decays is determined by fitting to the low energy spectrum, and it is found that there is accumulation on the surface of acrylic vessel.





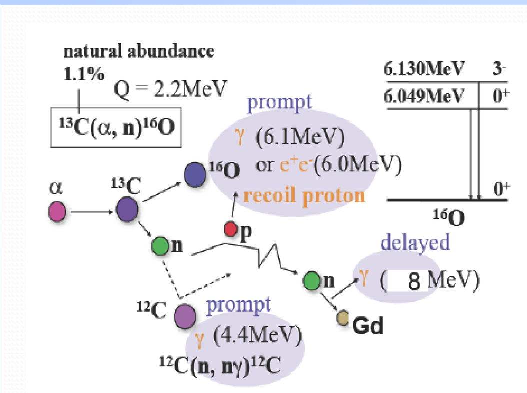
Rate	AD1	AD2	AD3	AD4	AD5	AD6	AD7	AD8
In GdLS	10.2	8.2	4.2	4.4	4.0	3.8	4.1	8.8
On IAV	9.9	7.8	4.0	4.2	3.9	3.7	3.9	8.3

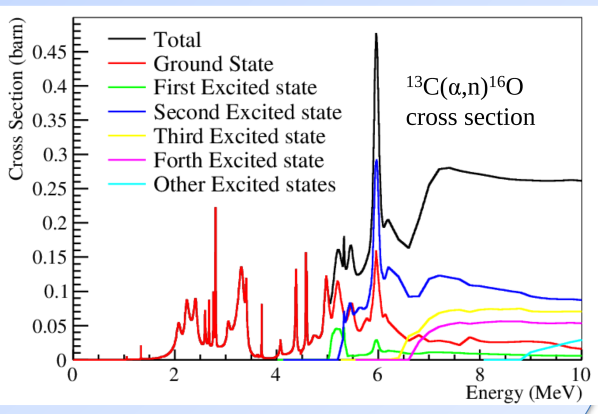
Different AD ^{210}Po rates are consistent to their exposure time in the air. For example, AD1 and AD2 are near half year while AD3 to AD6 are 2 months

$^{13}C(\alpha,n)^{16}O$ background

In a LS or Gd-LS detector, electron anti-neutrino is detected via Inversed Beta Decay (IBD), which has a prompt signal from positron and a delayed signal from neutron capture.

The $^{13}C(\alpha,n)^{16}O$ reaction can mimic IBD since it emits an energetic neutron, and prompt signal is formed by the neutron scattering on a proton, and delayed signal by neutron capture.



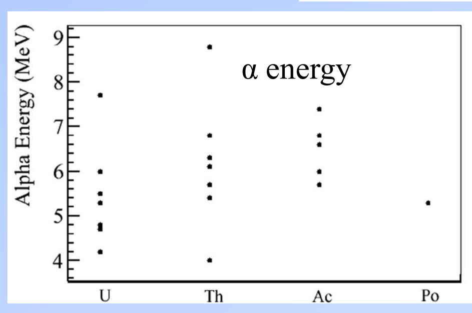


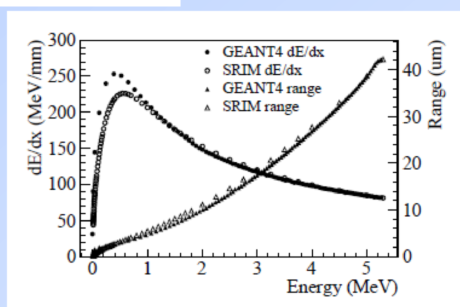
$^{13}C(\alpha,n)^{16}O$ rate

The neutron yield is calculated using the following equations:

$$N(E_\alpha) = \int_0^{Range_\alpha} \sigma(E(x)) N dx \quad (2)$$

$$= \int_0^{Range_\alpha} \sigma(E(x)) \cdot \frac{\rho_c}{Z_c} \cdot N_A dx \quad (3)$$





There is no analytic function for cross sections, so numerical integration is applied.

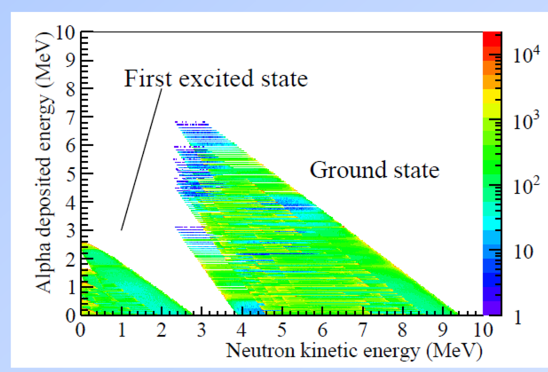
Step lengths and α range (right Fig) are simulated with GEANT4

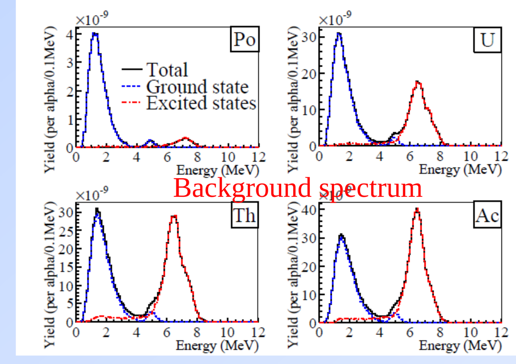
DecayChain	N_{ground}	$N_{excited}$	N_{total}	Uncertainty
^{210}Po	5.26e-8	4.90e-9	5.75e-8	7.2%
^{238}U	4.34e-7	2.96e-7	7.30e-7	16.9%
^{232}Th	4.49e-7	4.92e-7	9.41e-7	27.7%
^{227}Ac	4.72e-7	6.18e-7	1.09e-6	25.9%

$^{13}C(\alpha,n)^{16}O$ spectrum

Background spectrum is consisted of:

1) α kinetic energy deposit before the reaction
2.1) If neutron scattering with ^1H, recoil proton energy deposition
2.2) If neutron inelastic scattering with ^{12}C, 4.4MeV de-excited γ
3) If ^{16}O is at excited states, de-excited e^+e^- pair or γ





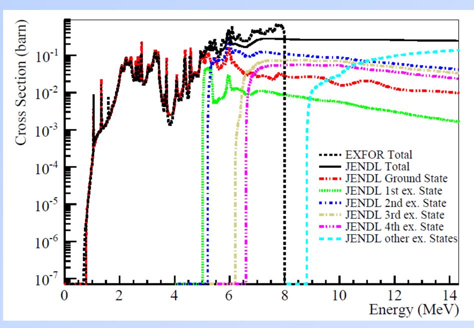
Steps to make the background spectrum:

1) Record neutron energy and α deposit energy before reaction (left plot)
2) Add the e^+e^- pair or γ from ^{16}O de-excited with a proper rate
3) Combine 1) and 2) to a generator and send to MC for simulation

Neutron yield uncertainty

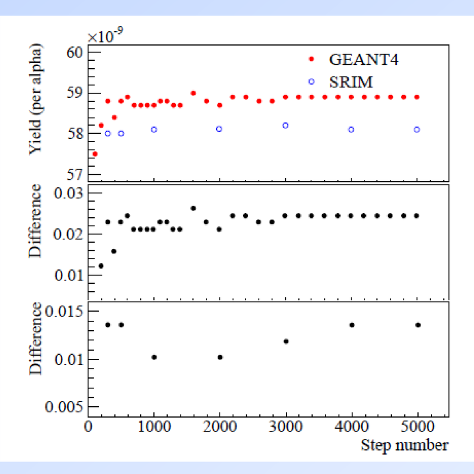
Neutron yield uncertainty is contributed by:

1) Cross section uncertainty
2) Uncertainty of α range and energy deposit density
3) Step lengths used in the integration



Each uncertainty source is examined

1) Neutron yield calculated with difference databases JENDL and EXFOR are compared
2) GEANT and SRIM are utilized to simulate α range and dE/dX (bottom panel of the lower plot)
3) Different step lengths are tested (middle panel of the lower plot)



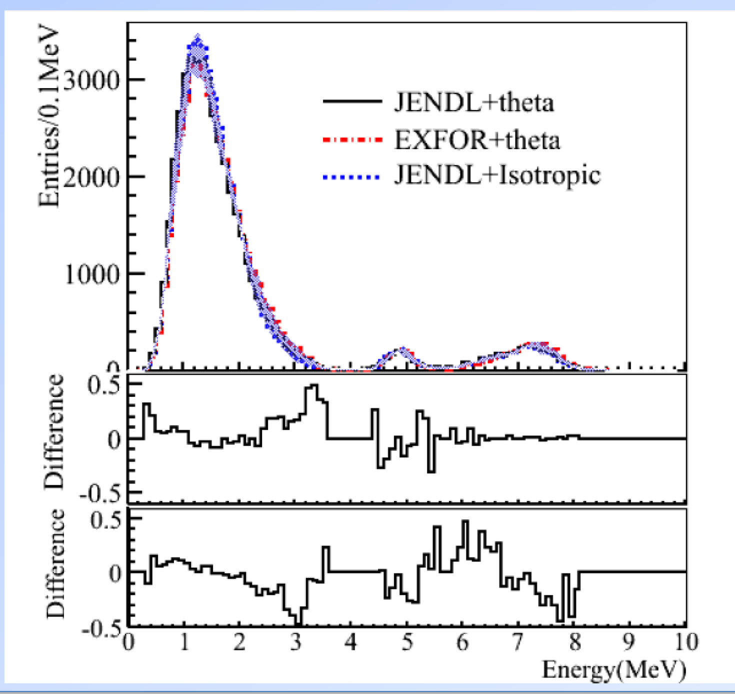
Note 1: absolute error of a database is not considered

Note 2: a certain experiment should include α rate error

Spectrum uncertainty

Uncertainty sources for spectrum are similar to that for neutron yield. We also examine one by one, and give a combined error band.

To a certain experiment, alpha rate uncertainty and difference between data and MC should be considered.



Summary

1) We report the analysis of cascade decays in the natural radioactivity decay chains, and determine rates of the chains
2) We report the observation of high rate ^{227}Ac decay chain in the Gd-LS detector, and estimate the purification of $GdCl_3$ removes ^{238}U by 480 times
3) We fit the low energy spectrum to get the ^{210}Po decay rates, and find it is accumulated on the surface on acrylic vessel, and the accumulated rate is proportional to the exposure time in air.
4) We calculate the neutron yield from difference decay chains and generate the background spectrum. We also estimate the uncertainty of yield and spectrum.

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On behalf of the Daya Bay Collaboration