Identifying $\overline{\nu}_e$ with Super-Kamiokande: GADZOOKS! *status and remaining issues*

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Super-Kamiokande (SK) has been and continues to be one of the most successful experiments in neutrino physics. However, SK cannot distinguish neutrinos from anti-neutrinos, a crucial capability for several very important SK measurements. Being able to do so would improve dramatically SK's sensitivity to Supernova Relic Neutrinos since its currently overwhelming spallation background could be largely suppressed, and it would also enable a precise determination of solar elements of the leptonic mixing matrix from reactor neutrinos.

For that purpose SK is carrying out EGADS, a GADZOOKS! R&D project. The idea is (Beacom and Vagins, 2004) is to dissolve in the water a compound of Gadolinium (Gd), the element that has the largest cross section for neutron capture, process that is followed by the emission of few gammas adding up 8 MeV energy. The Gd would allow SK to identify anti-neutrinos interacting via inverse beta decay, by coincident signals from the charged anti-lepton and the delayed 8 MeV γ cascade.

This technique could have a serious drawback if the Gd compound brings with it a sizable contamination of natural radioactivity. We are thoroughly studying this potential problem by analyzing the different background-producing final states induced by the spontaneous fission of the ^{238}U and by the α particles from the α-decays in the decay chains. We are estimating the amount of radioactive contamination that SK with Gd can afford, and are investigating reconstruction algorithms that could maximize the discrimination between anti-neutrino signal and radioactivity-induced background.

Introduction

- SK is a 50 kton water Cherenkov detector in the Kamioka Mine, Japan
- SK began its search for proton decay and neutrino physics studies in 1996
- Important is the CCQE scattering of the incoming ν with nucleons in water

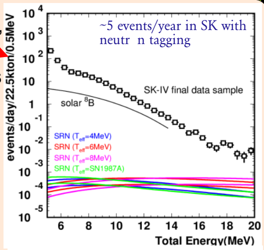
$$\nu_\alpha + n \rightarrow l_\alpha + p \qquad \overline{\nu}_\alpha + p \rightarrow \overline{l}_\alpha + n$$

- Nowadays, SK cannot distinguish (efficiently) $\overline{\nu}$ from ν because it is not able to detect either **n**eutrons nor **p**rotons (the latter at low energy)
- This distinction would be of most importance for deeper study of ν properties

→ **try neutron tagging**

New physics reach

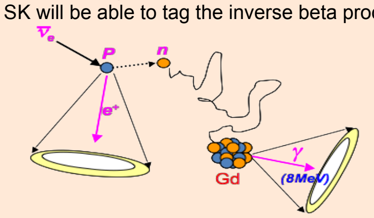
- Diffuse Supernova Neutrino Background (**DSNB**), currently limited by background $\overline{\nu}_e + p \rightarrow e^+ + n$
- Improve sensitivity to solar sector oscillation parameters
  - ⇨ neutron tagging would increase substantially the rate compared to the KamLAND reactor
- proton decay: no neutron should be in the final state
- Sensitivity to "wrong sign" ν_e production from Sun
- Much more detailed measurement of nearby Supernovae explosion
- Gain information on the hadronic final states of νs interactions
- Maybe distinction between $\overline{\nu}$s and νs from T2K
- Identification of $\overline{\nu}$ over ν in the atmospheric sector (~GeV) is being studied



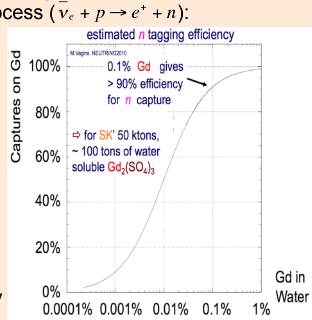
Points show current background rate due to spallation and ^{8}B flux, and color lines show different DSNB predictions

GADZOOKS! project

- **neutron tagging** in Super-Kamiokande
- **Gad**olinium has the greatest **n** capture cross section of all stable nuclei
- When **Gd** captures a thermalized **n**, it emits a γ cascade of **8 MeV**
- SK will be able to tag the inverse beta process ($\overline{\nu}_e + p \rightarrow e^+ + n$):



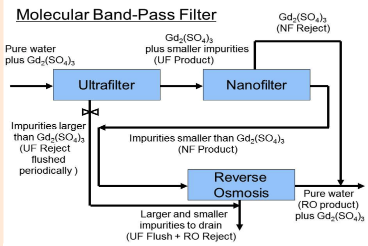
- A water soluble **Gd** compound added to WC detectors would greatly improve their performance via delayed coincidence
- $Gd_2(SO_4)_3$: no corrosion, excellent solubility and small light attenuation



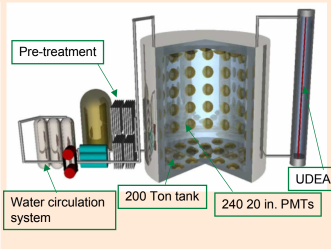
[Beacom and Vagins PRL93,171101 (2004)]

EGADS

- Selective filtration system (brand new technology developed at UCI)
- Gd compound "cleaning" and dissolving → pre-treatment system circulation thorough resins (AJ4400 to remove U, Th)
- Water transparency monitoring → UDEAL (**U**nderground **D**evice **E**valuating **A**ttenuation **L**ength)
- Check Gd volume uniformity → AAS (**A**tomic **A**bsorption **S**pectrometer)
- Gd removal



Scheme of the water filtration system, which purifies water keeping the Gd



Backgrounds of GADZOOKS!

- An important source of background comes from the radioactive contamination of the materials; of clear relevance is that in the **Gd**…
- We study thoroughly these backgrounds:
  - their intensity given the measured radioactivities
  - their impact on the new physics measurements
  - their impact on the traditional SK measurements
- the complete campaign of radioactivity for GADZOOKS! is carried out at the LSC (Canfranc Underground Laboratory) using HPGe detectors

neutrons from (α,n)

- **(α,n)** reactions with **^{18}O**
  - α particles are emitted with ~6 MeV

$$^{18}O + ^4\alpha(\sim 6 MeV) \rightarrow ^{22}Ne^*(\sim 15 MeV) \rightarrow ^{20}Ne + 2\,^1n(\sim 2.5 MeV)$$

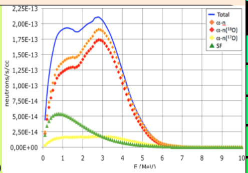
⇨ neutrons come in pairs and no γs are emitted

- Similarly occurs with **^{17}O** case, but

$$^{17}O + ^4\alpha(\sim 6 MeV) \rightarrow ^{21}Ne^* \rightarrow ^{19}F + 2\,^1n(\sim 2.6 MeV) + \gamma(0.4 MeV) + \beta(1.5 MeV)$$

⇨ neutrons come in pairs

⇨ γs and βs are too weak to be detectable

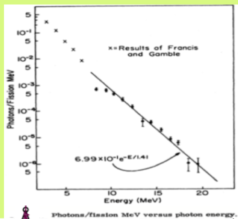


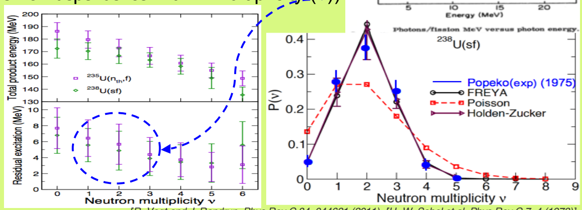
Neutron production spectrum, split into: Spontaneous Fission (green), α-n reactions with ^{17}O (yellow), α-n with ^{18}O (red), total of α-n reactions (orange) and total neutron production (blue)

(α,n) are distinguishable from inverse beta… But produce many neutrons

[1γ + 1n] events from Spontaneous Fission

- **^{238}U** the greatest contribution to **SF**
  - emits neutrons and photons
  - fraction of **SF** in **^{238}U** is $5\cdot10^{-7}$
  - probability of a γ ray from **^{238}U SF** with a given energy is $P(E)=0.7e^{-E/1.4}$
  - probability of 1**n** per fission is *28%*
  - (E_γ small dependence with **n** multiplicity (ν))





[R. Vogt and J. Randrup, Phys.Rev.C 84, 044621 (2011)], [H. W. Sobel et al, Phys.Rev.C 7, 4 (1973)]
[A.G.Popeko, V.I.Smirnov, G.M.Ter-Akopyan, B.V.Fefilov,JNuclPhys 24 1976 473, Sov. J. Nucl. Phys. 24 1976 245 (18/06/1975)]

⇨ 60 [γ + n] events/year

- AJ4400 reduces the amount of **^{238}U** by a factor 100
  - ⇨ 0.6 [γ + n] events/year after AJ4400 processing
- current **$Gd_2(SO_4)_3$** batch at EGADS ⇨ <2 [γ+n] events/year with AJ4400

γs and βs

- Other elements of radioactive chains decay by emitting βs
  - Some elements emit βs with sufficiently high energy accompanied by γs
    - $^{232}Th \rightarrow \ldots \rightarrow ^{228}Ra \rightarrow \ldots \rightarrow ^{208}Tl \rightarrow E_\beta^{max}=5.0$ MeV + γ 583 keV 84%, γ 861 keV 12%, γ 2615 keV 99%
    - $^{238}U \rightarrow \ldots \rightarrow ^{226}Ra \rightarrow ^{222}Rn \rightarrow \ldots \rightarrow ^{214}Bi \rightarrow E_\beta^{max}=3.3$ MeV + γ 609 keV 46%, γ 1120 keV 15%, γ 1765 keV 16%
  - To achieve **4.0 MeV** solar neutrino analysis in 0.1%Gd+H_2O SK
    - < 0.35 mBq/kg [**^{238}U**]
    - < 0.35 mBq/kg [**^{232}Th**]
  - we also need to remove the **Ra** from Gd compound
    - Selective resins, such as DOWEX RSC, are one available solution

Summary / Conclusions

- Neutron tagging would improve dramatically the sensitivity of SK
- Gd very good candidate to do the job
- $Gd_2(SO_4)_3$ best compound in terms of solubility and corrosion
- Tests done with $Gd_2(SO_4)_3$ show
  - no Gd rejection due to the selective filtration system: success!
  - very good water transparency
  - solution uniformity very good
- Studied backgrounds from radioactive contamination
  - (α,n) produce many **n** but no high energy γs
  - background from ^{238}U **S**pontaneous **F**ission implies that we must reduce U contamination in Gd salt. AJ4400 removes U with high enough efficiency
  - βs and γs from ^{208}Tl and ^{214}Bi implies we must reduce Ra levels

invisibles
neutrinos, dark matter & dark energy physics