The CeLAND experiment

Journées Jeunes Chercheurs 2013

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Outline

1. Neutrino and oscillations
   - Oscillations (that we understand)
   - Oscillations (that we try to understand)
2. The CeLAND project
   - The CeLAND source
   - The CeLAND detector
3. The first simulations (my work)
   - Signal
   - Backgrounds
4. Conclusion

The neutrino

- First infered by Pauli in 1930 to explain β decay missing energy
- Discovered in 1956 (reactor neutrinos)
- Weakly interacting particles $\rightarrow$ Very low interaction cross-section $\rightarrow$ Very hard to detect

Open questions: Leptonic CP violation, mass, mass hierarchy, Dirac or Majorana, additionnal flavors...?

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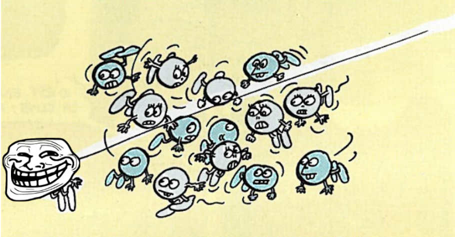

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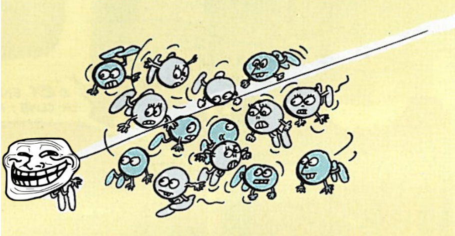

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Neutrino oscillations

- Infered in 1957 by Pontecorvo and discovered in 1998 by Super-Kamiokande (atmospheric ν's)
- Neutrinos have mass and oscillate between 3 flavors ν_e, ν_μ, ν_τ via the PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

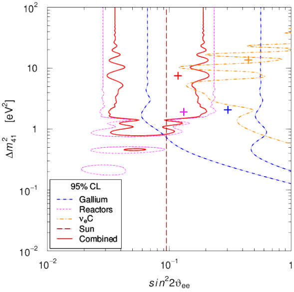
$\sin^2 2\theta_{23} \sim 1$ — Atmospheric ν's

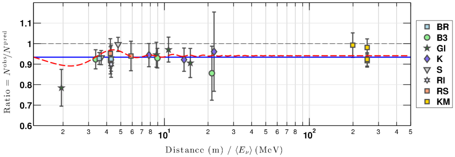
$\sin^2 2\theta_{13} \sim 0.1$ — Reactor ν's

$\sin^2 2\theta_{12} \sim 0.8$ — Solar ν's

Oscillation anomalies

- Anomalies found in several experiments:
  - Accelerator experiments (LSND, MiniBoone)
  - Source experiments (Gallex, SAGE)
  - Reactor experiments (Bugey, Rovno, ILL,...) $\rightarrow$ Reactor Antineutrino Anomaly (RAA)
- $\rightarrow$ Lead towards the existence of a 4^{th} neutrino, sterile (no weak interaction) and heavy ($\sim$ eV scale)
- Possible candidate for BSM physics





4^{th} neutrino hypothesis

- 3 (ν_e, ν_μ, ν_τ) + 1 (ν_s) oscillation → Simple calculations using 2-neutrino (ν_e, ν_s) oscillations

$$\begin{pmatrix} \nu_e \\ \nu_s \end{pmatrix} = \begin{pmatrix} C_{new} & S_{new} \\ -S_{new} & C_{new} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_{new} \end{pmatrix}$$

After calculations → $P_{ee} = 1 - \sin^2 2\theta_{new} \sin^2 \frac{\Delta m^2_{new}(eV^2)L(m)}{E(MeV)}$

Sterile neutrino parameters: $\sin^2 2\theta_{new} \sim 0.1$ and $\Delta m^2_{new} \sim 2\ eV^2$ → Gives an oscillation length of a few meters

→ Need to test this anomaly at ∼ 10 m (corresponds to $E = 1\ MeV$)

Testing $\bar{\nu}_e$ disappearance anomalies

- Need a powerful source of $\bar{\nu}_e$ close to a detector $\rightarrow$
  - Nuclear reactor + ton scale detector $\rightarrow$ Nucifer, Stereo
  - Radioactive source + kiloton scale detector $\rightarrow$ CeLAND
- Source experiments advantages $\rightarrow$
  - Search for an oscillation pattern in both distance and energy (shape analysis)
  - Search for an expected neutrino deficit (rate analysis)
  - Compact source + Good vertex resolution $\rightarrow$ Good sensitivity to Δm^2_{new}
  - Powerful source + Big well-known detector $\rightarrow$ Few % uncertainties (stat. + syst.) $\rightarrow$ Good sensitivity to $\sin^2 2\theta_{new}$
- CeLAND design
  $\rightarrow$ **75 kCi (2.8 PBq !) $\bar{\nu}_e$ generator in the KamLAND neutrino detector**

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The CeLAND collaboration

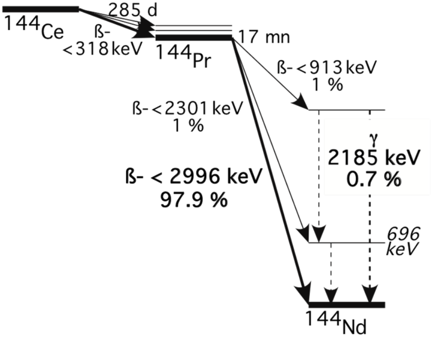
- Commissariat à l'Energie Atomique, Centre de Saclay, France
- Astroparticules et Cosmologie, APC, Université de Paris 7, France
- Research Center for Neutrino Science, Tohoku University, Japan
- Colorado State University, Fort Collins, USA
- Kavli Institute, University of Tokyo, Japan
- Lawrence Berkeley National Laboratory, Berkeley, USA
- University of California, Berkeley, USA
- Nikhef and the University of Amsterdam, Netherlands
- North Carolina Central University, Durham, USA
- Graduate School of Science, Osaka University, Japan
- Center of Theoretical and Experimental Physics, Moscow, Russia
- Frumkin Institute of Physical chemistry and Electrochemistry, Russia
- University of Hawaii at Manoa, Honolulu, USA
- University of North Carolina, Chapel Hill, USA
- University of Tennessee, Knoxville, USA
- University of Washington, Seattle, USA

$\sim$ 60 persons in 18 institutes worldwide

CeLAND ^{144}Ce-^{144}Pr source

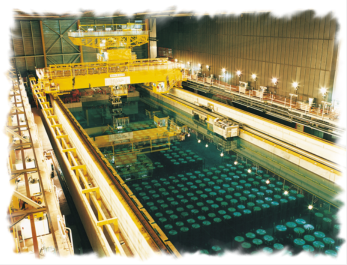
- Source emitting $\bar{\nu}_e$ by β-decay
- Need energetic $\bar{\nu}_e$ $\rightarrow$ High Q-value
- Need enough time for transportation $\rightarrow$ Reasonable half-life $\rightarrow$ Contradictory statements
- Solution $\rightarrow$ ^{144}Ce-^{144}Pr pair

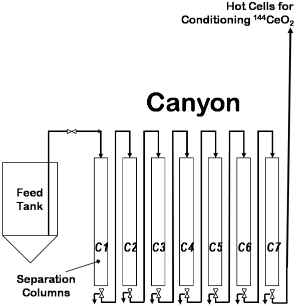
  $\rightarrow$ Gives $\bar{\nu}_e$ up to 2.6 MeV and half-life of $\sim$285 days



Source production

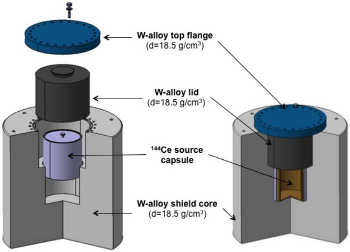
- Cerium is a rare earth found abondantly ($\sim$ 5%) in spent nuclear fuel
- Production at Mayak PA (Russia) reprocessing facility using fresh irradiated fuel from the Cola Power plant
- 10 t of fuel $\rightarrow$ 25 g of ^{144}Ce (75 kCi)
- ^{144}Ce extraction using chromatography ($\sim$4-6 months)





Source shielding

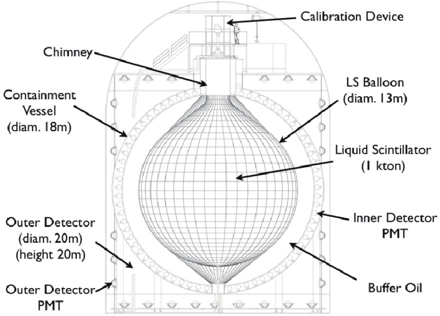
- Several γ rays emitted through ^{144}Pr decay $\rightarrow$ 1.489 MeV (0.3 %) and 2.185 MeV (0.7 %)
- Shielding needed for physics (background reduction) and safety (radiation dose)
- Design $\rightarrow$ 16 cm thick cylinder of tungsten alloy ($d = 18.5\ g.cm^{-3}$)



Dose calculations

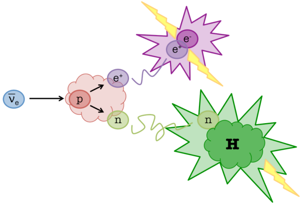
- Goal: Determine the absorbed dose received around the shielding
- First approximations obtained using analytical computations: $D(J/g/s) = \mathcal{A}[Bq] \times \frac{1}{4\pi d^2[cm^2]} \times \frac{\mu}{\rho}[g/cm^2] \times E[J]$
- Cross-checked using particle simulation codes
- Results: Absorbed dose of 42 μSv.h^{-1} 1 m away from the shielding (maximum dose for workers: 20 mSv.yr^{-1})

The KamLAND detector



- Large scale liquid scintillator detector located in the Kamioka mine (Japan) since 1998
- 1 kton of scintillator oil (6.5 m sphere) + 2 m thick buffer (non-scintillating)
- 3.2 kton of water as external radioactivity shield and Cerenkov muon veto
- 1879 PMT's $\rightarrow$ Good vertex and energy resolution

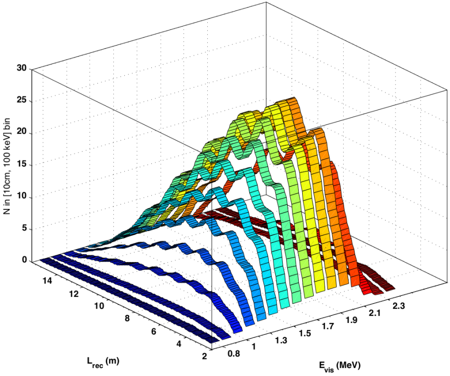
How to detect $\bar{\nu}_e$ in KamLAND ?

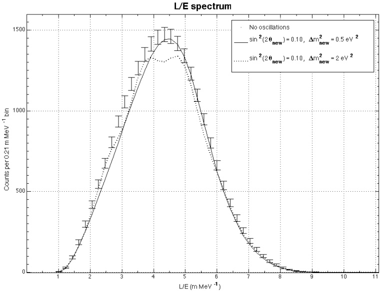


- Inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$
- Higher cross section than other ν interactions $\sigma_{IBD} \sim 10^{-43} cm^{-2}$
- Signature $\rightarrow$ Prompt signal (e^+ energy deposition) followed by delayed signal (neutron capture on H at 2.2 MeV)
- Look for: Energy signature (0.9 to 2.6 MeV for prompt, 1.8 to 2.6 MeV for delayed), time and space coincidence $\rightarrow$ Huge background reduction !

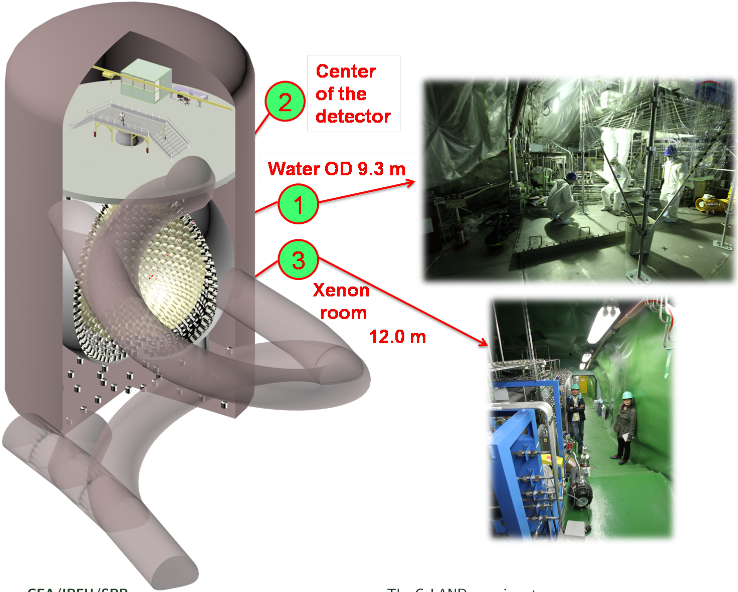
What do we expect as a signal ?

Neutrino deficit dependant on the energy and distance to the source





Source deployment in KamLAND



CeLAND agenda

- 2014: Source production @ Mayak (up to 6 months)
- Early 2015: Transportation and deployment in KamLAND (phase 1)
- 2016: Possible deployment at KamLAND center (phase 2)

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CeLAND simulations

- Signal and backgrounds simulations needed to caracterize sensitivity
- Use of Geant4 and Tripoli4 (Monte-Carlo particle transport simulation codes)

Signal

- $\bar{\nu_e}$ energy as seen in KamLAND (oscillated or not)
- Dependent on the source-detector distance (different CeLAND phases)

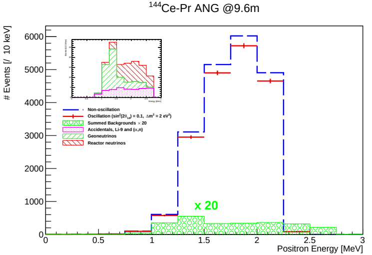
Backgrounds

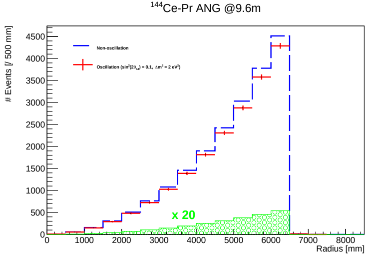
- KamLAND 'regular' backgrounds (already measured)
- Source backgrounds (to be determined)

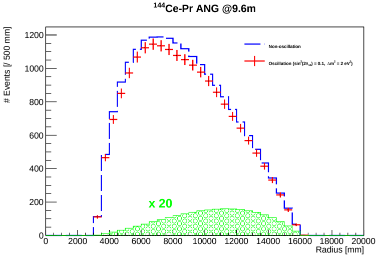
Signal simulations

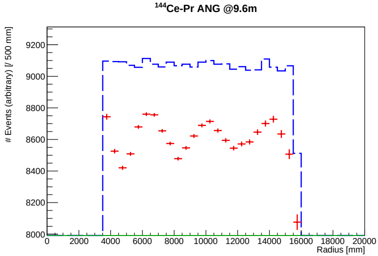
- Geant4 does not handle $\bar{\nu_e}$ interaction $\rightarrow$ Need to create an $e^+ - n$ pair
- Oscillation parameters: $\sin^2 2\theta_{new} = 0.1$ and $\Delta m^2_{new} = 2\ eV^2$
- Normalized to the ~20000 events expected within a year

Signal simulations - Results









Backgrounds simulations

- KamLAND backgrounds:
  - Natural radioactivity
  - Cosmogenics (muon induced radioactive isotopes)
  - Reactor $\bar{\nu}_e$
  - Geoneutrinos

  → These backgrounds have been measured precisely by KamLAND

  → Almost negligible wrt CeLAND expected signal
- CeLAND backgrounds:
  - Gamma rays from the source
  - Neutrons from spontaneous fission of residual fission products

→ Potentialy dangerous

→ Need to be simulated in order to specify the appropriate contamination in neutron emitter impurities

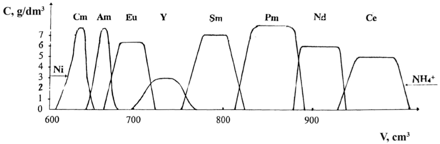
Gamma background

- Random γ interaction $\rightarrow$ Could mimic a prompt or a delayed (or both) signal $\rightarrow$ Fake neutrino event !
- Source gamma activity = 20 TBq !
- Attenuation of at least 10^{12} needed to achieve a reasonable S/B ratio
- 16 cm of tungsten + 2 m of buffer oil should be enough $\rightarrow$ Simulations will give exact attenuation and detected energy spectra

- Hard task: 1 s of 'experiment time' (20×10^{12} gammas) $\rightarrow$ 200 000 hours of simulations !

Neutron background

- Fuel irradiation can produce small amounts of heavier elements by neutron capture reactions
- However, the chromatography process purifies a lot of these actinides. But how much ?



These elements (Cm, Cf,...) are likely to undergo spontaneous fission reactions ($X \rightarrow Y + Z +$ several neutrons)

$\rightarrow$ Potential source of background

Neutron background

- Neutrons can be thermalized and captured around or in the detector
- They are emitted in coincidence $\rightarrow$ Time correlation $\rightarrow$ Perfect mimic a a neutrino event
- Hard to shield neutrons (need light elements such as H to thermalize and high capture cross-section elements such as boron)
- Need simulations to evaluate the impact of this background and whether we should shield it or not ?

Geant4 vs Tripoli4

- Geant4: Complete simulation, keep tracks, secondary particles, etc..
  → Ressources consuming
- Tripoli4: No tracks, easy to bias → Faster computation
- Seems like:
  - Geant4 → Suited for neutron simulations
  - Tripoli4 → Suited for gamma simulations
- However ! Geant4 handles neutron processes quite badly → Need Tripoli4 cross-check (used for reactor core simulations)

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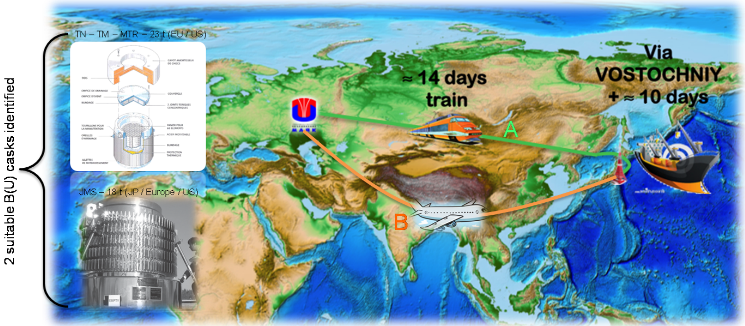
Conclusion

- Simulations still ongoing to determine the impact of gamma+neutron background
- Preliminary results: 16 cm of tungsten + at least 10 cm of borated water might be needed
- New Tripoli4 simulations will give a definitive answer soon

Thanks

Thank you for your attention !

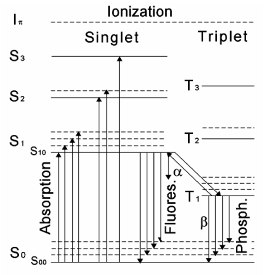
Source transport



- Option A: Train from Mayak to Vladivostok + boat to Tokyo + truck to KamLAND ($\sim$ 4 weeks)
- Option B: Plane from Mayak to Japan + truck to KamLAND ($\sim$ 2 weeks)

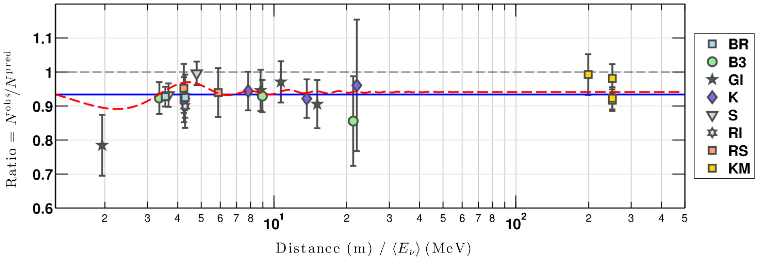
Liquid scintillators

- Scintillation: Process by which ionization produced by charged particles excites a material and light is emitted by the de-excitation
- Liquid scintillators: Organic scintillator diluted in an optically-inert liquid (mineral oil,..)
- Basically: Charged particle ionizes liquid → Excites molecules that de-excites emitting light
- This light is detected using photomultiplier tubes (PMT's) that transforms it into a current



The reactor antineutrino anomaly (RAA)

- Revised calculation of the $\bar{\nu_e}$ rate from nuclear reactors → 3.5 % $\bar{\nu_e}$ deficit
- New $\bar{\nu_e}$ cross-sections → Another 3.5 % $\bar{\nu_e}$ deficit
- This new flux gives a mean $\bar{\nu_e}$ deficit of $R^R = 0.927 \pm 0.023$ $(3\ \sigma)$ for 19 previous short range experiments



Another project: STEREO

- Other sterile neutrino project developped at CEA (SPhN) → See Maxime Pequignot's talk
- Based on the Nucifer experiment → Small detector close to a research reactor (ILL @ Grenoble)
- Idea: Look for the oscillation pattern using a segmented detector → Difference of rate and spectral shape in different sections
- Challenges: Deployment that close to a nuclear core and high neutron background