



Reactor anti-neutrino & Non proliferation

- Saclay (SPP+SPhN) + Nantes
- Institut Kurchatov (russie) + USA (Sandia)

International Atomic Energy Agency (IAEA)

Its role :

- ✗ Controls for international community that its member states don't use civilian nuclear installations for military purposes
- ✗ checks the application of the Non Proliferation Treaty
- ✗ Inspects nuclear installations of more than 140 states

Actual means of control :

Non destructive analysis : γ spectroscopy, neutron counting

Destructive analysis, isotopic determination, environmental measurements

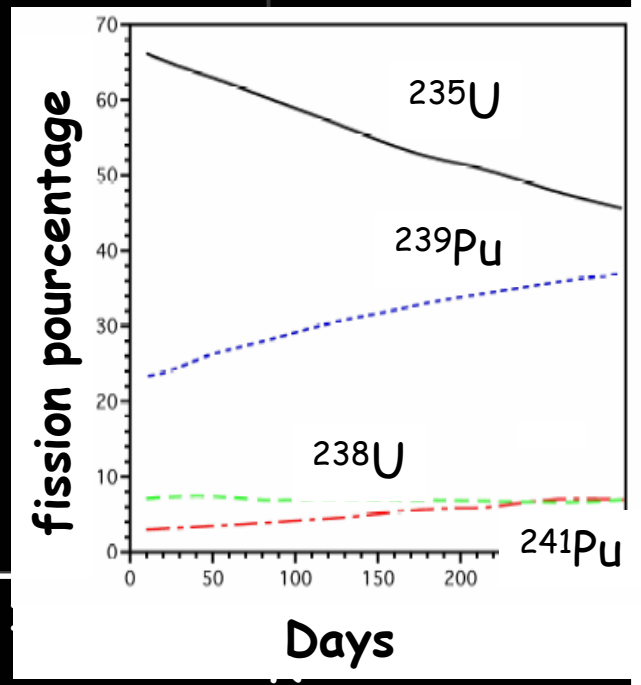
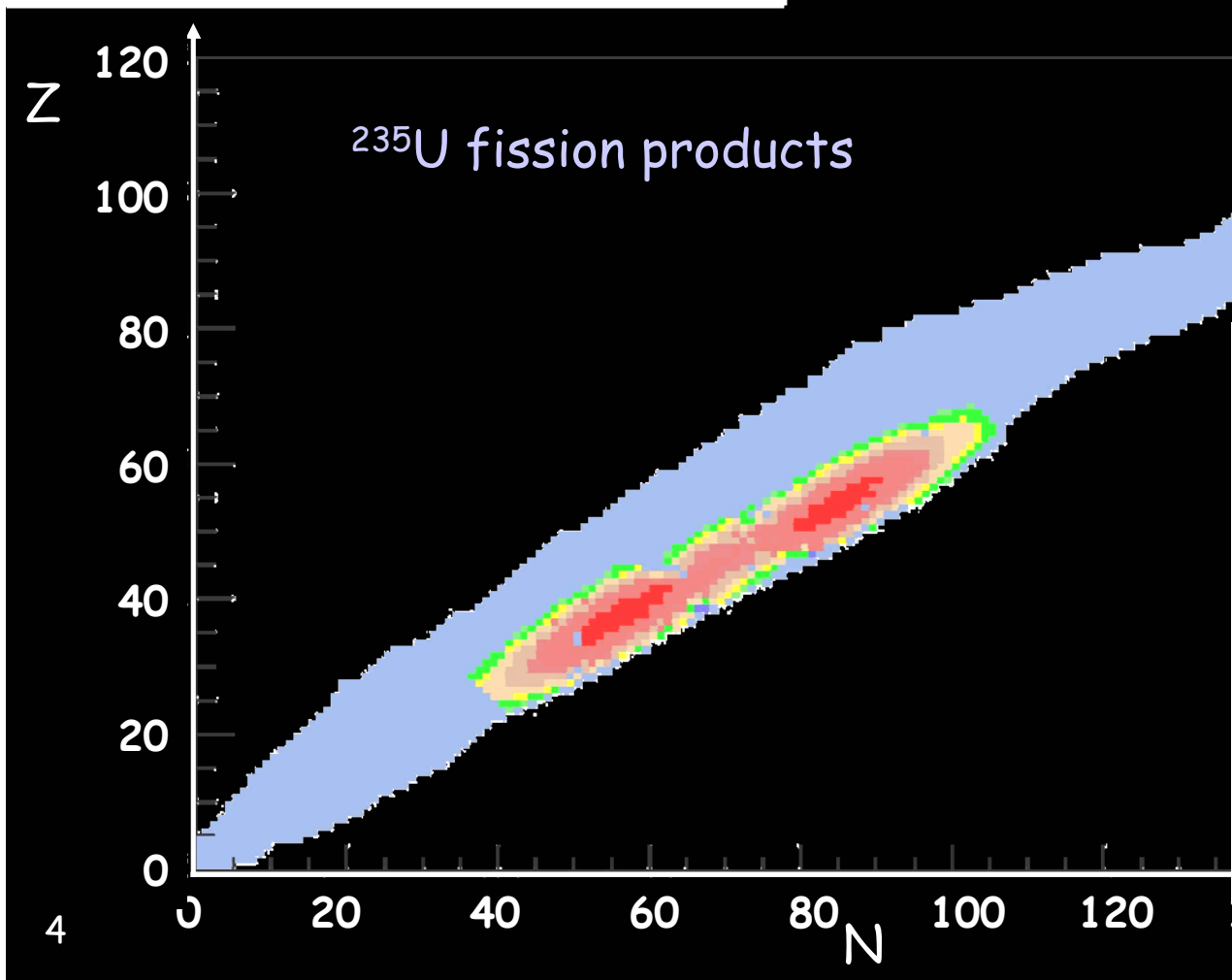
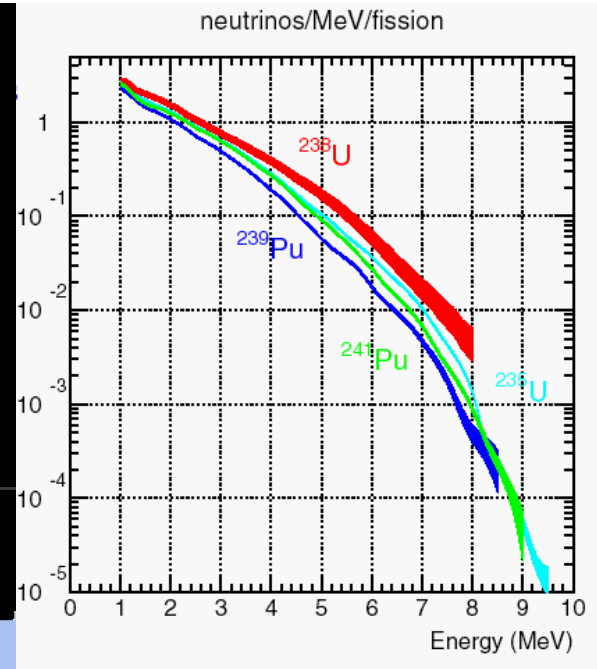
Neutrinos for non-proliferation ?

- Antineutrinos can not be shielded
- Reactors produce very large amounts of antineutrinos which reveal fissile composition
- Remotely monitor real-time reactor state
- Only monitor fissioning material
- Antineutrinos interact weakly thus detectors must be large and close to reactor



IAEA recommends a feasibility study on ν potential

	^{235}U	^{239}Pu
released energy per fission	201.7 MeV	210.0 MeV
Mean energy of ν	2.94 MeV	2.84 MeV
ν per fission > 1.8 MeV	1.92	1.45
average inter. cross section	$\approx 3.2 \cdot 10^{-43} \text{ cm}^2$	$\approx 2.76 \cdot 10^{-43} \text{ cm}^2$





ν Detectors: A New Safeguards Tool ?

- **Undeclared production of fissile materials** (referent diversion : $\sim 10\text{kg}$ of ^{239}Pu , $\sim 1\text{m}^3$ @10-25m, detection time < 3 months)
 - Complicated diversion scenarios \rightarrow partnership IAEA (PWR, Generation III & IV reactors)
 - Need of :
 - A very precise neutrino detector close to a power plant
 - New measurements of neutrino spectra
 - Very difficult - Need a careful study
- **Total burn-up and reactor power control**
 - Thermal power is not monitored by AIEA
 - Relevant potentiality for reactor ν
- **Detection of undeclared reactor**
 - « KamLAND » like sub-marine detector
 - Control at the level of a country
 - Seems possible in a no-cost world ... But very vulnerable !
- **Monitoring of large spent fuel elements :**
 - Antineutrino detectors = only measurements on large quantities of beta emitters (several cores of spent fuel).
 - During Double Chooz : discharge of parts of the core \Rightarrow quantify the sensitivity of such monitoring.

Required accuracy ?

P. Huber & T. Schwetz, hep-ph/0407076,
Precision spectroscopy with reactor antineutrinos

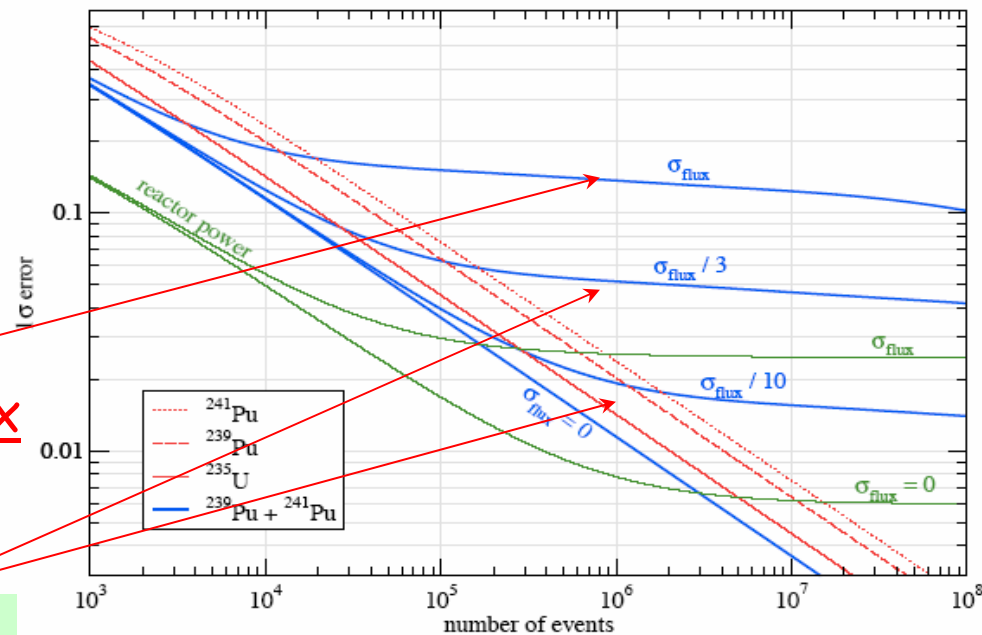
- New parameterization : 6 coefficients instead of 3 (Vogel. et al.)
For ^{235}U , ^{239}Pu , ^{241}Pu and ^{238}U unchanged since not measured but calculated

10^6 evts : 10 tons @ 10m
in 10d

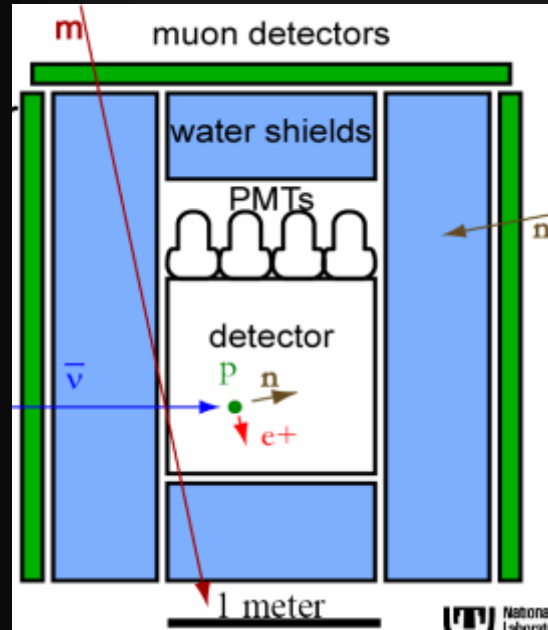
Power determ. in 1d @ 3%

Pu content poorly determ.
@ > 10% in 10d with
present knowledge of flux

Improve flux determ.

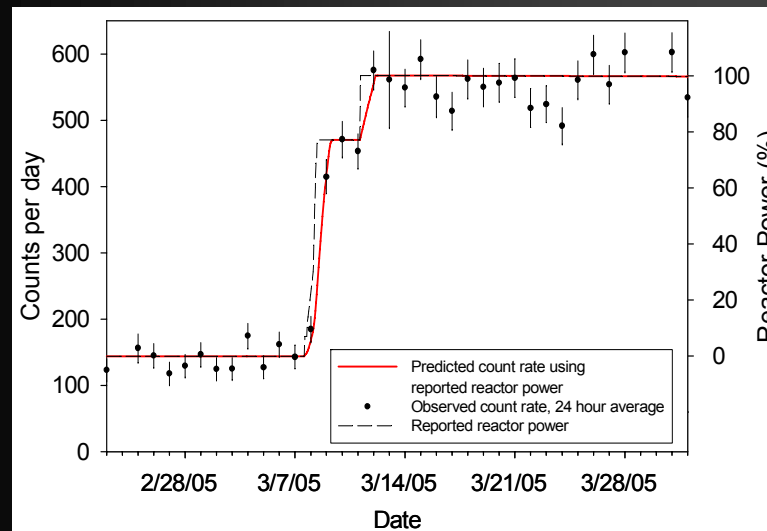


SANDS experiment



- 1 m³ Liquid scintillator central detector (Palo Verde scintillator)
- 2 PMTs covering top-side/tank, 2 tanks
- 6-sided water shield
- 5-sided active muon shield

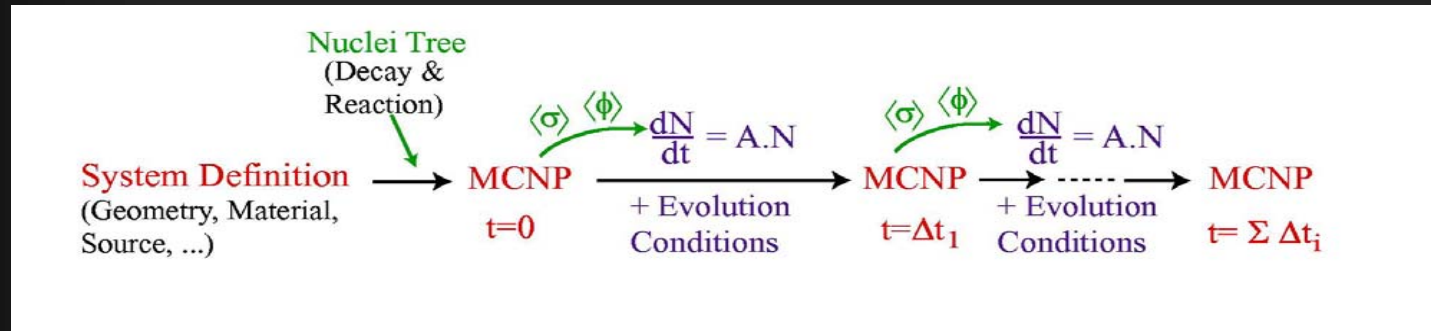
- 25 m from Unit 2
- 3.4 GWt reactor
- 6×10^{20} v/s



- Simple antineutrino detectors can be used to monitor nuclear reactors remotely and non-invasively
- Currently see ~ net 400 antineutrinos / day
- Full detector is 3 m x 3 m x 3 m
- Detector operates 24 hours / day with minimal intervention (monthly visits) and no burden on SONGS
- Working to improve detector stability to be able to see burnup, but already preliminary results

Fission products proportions vary with the fuel burn-up (so with time).

⇒ Need for « dynamical » calculation to simulate the evolution of fuel composition and the decay chains of the fission products



⇒ Aim = Simulation of the anti-neutrino spectrum built from the fission products spectra



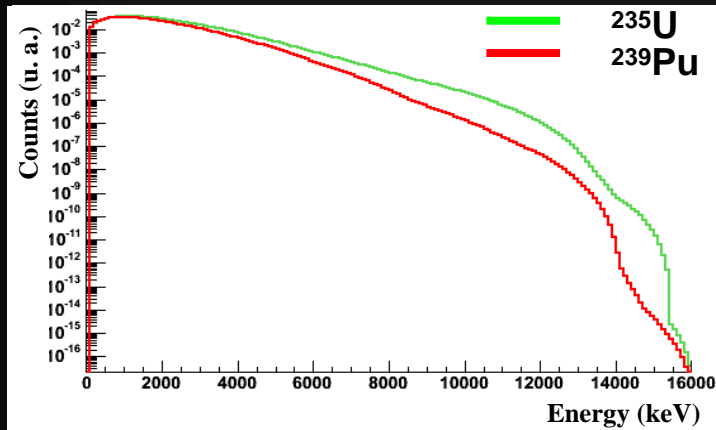
MCNP Utility for Reactor Evolution



MCNP Utility for Reactor Evolution



Influence of β -inverse decay cross-section on $\bar{\nu}_e$ spectrum

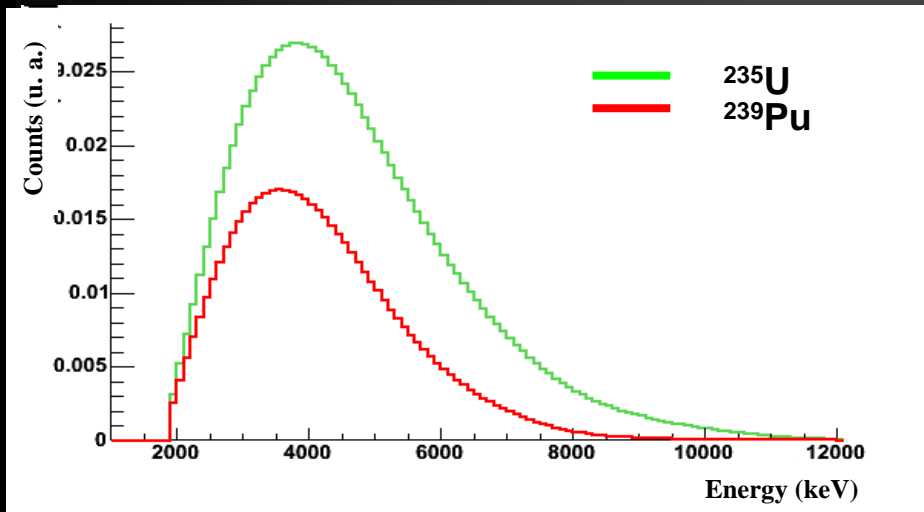


Simulated spectra of emitted antineutrinos using MURE :

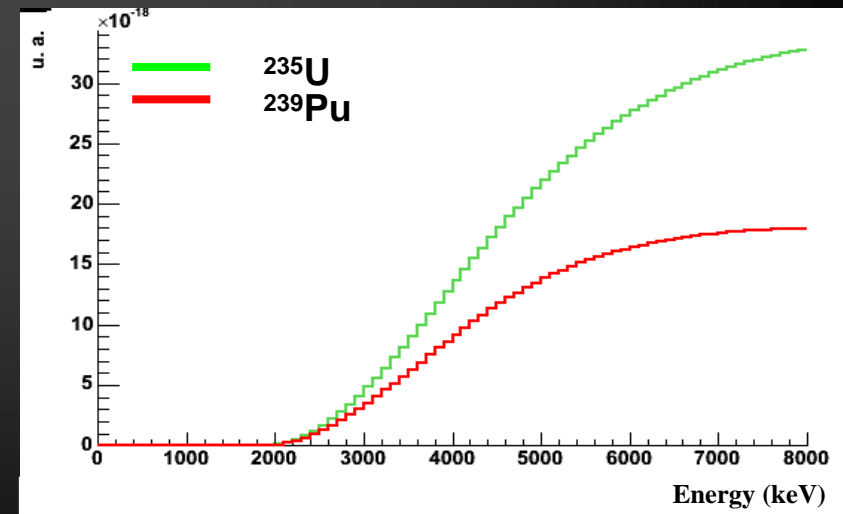
(Normalized to the same number of fissions)

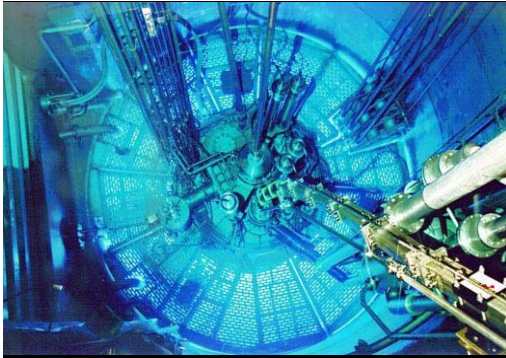
Folding with the detection cross section

$\bar{\nu}_e + p \rightarrow n + e^+$ Threshold : 1.804 MeV



Cumulative antineutrino energy spectrum folded by the detection cross section





Starting an experimental program...

✗ **Theoretical approach** : Klapdor & Metzinger microscopic calc. of trans. matrix elements (PLB82 + PRL82), Vogel et al. for ^{238}U

✗ **Integral β -spectra** measured by Schreckenbach et al. (at better than 2% until 8 MeV) & Hahn et al. @ILL ^{235}U , $^{239,241}\text{Pu}$ targets, but antineutrinos deduced from a global fit including 30 arbitrary contributions : global shape uncertainty from 1.3%@3MeV to 9%@8MeV

✗ **FP contributions** : measurements of Tengblad et al. 111 nuclei @ISOLDE don't agree with the experimental integral spectra (important errors : 5% at 4MeV, 11% at 5MeV and 20% at 8MeV)

✗ **Chooz and Bugey** : energy spectrum and flux in agreement with Schreckenbach et al. + Vogel et al., 1.9 % error on reactor ν_e flux

According to Bemporad et al. unknown decays contribute as much as 25% of the antineutrinos at energies $> 4\text{MeV}$!!?
(Bemporad et al., Rev. of Mod. Phys.74 2002)



First list of n-rich nuclei : ^{86}Ge , $^{90-92}\text{Se}$, ^{94}Br , $^{94-98}\text{Kr}$, ^{100}Rb , $^{100-102}\text{Sr}$, $^{108-112}\text{Mo}$, $^{106-113}\text{Tc}$, $^{113-115}\text{Ru}$, $^{130-131}\text{Cd}$...



✘ Test experiment @ Institut Laue-Langevin High Flux Reactor (Grenoble) last summer :

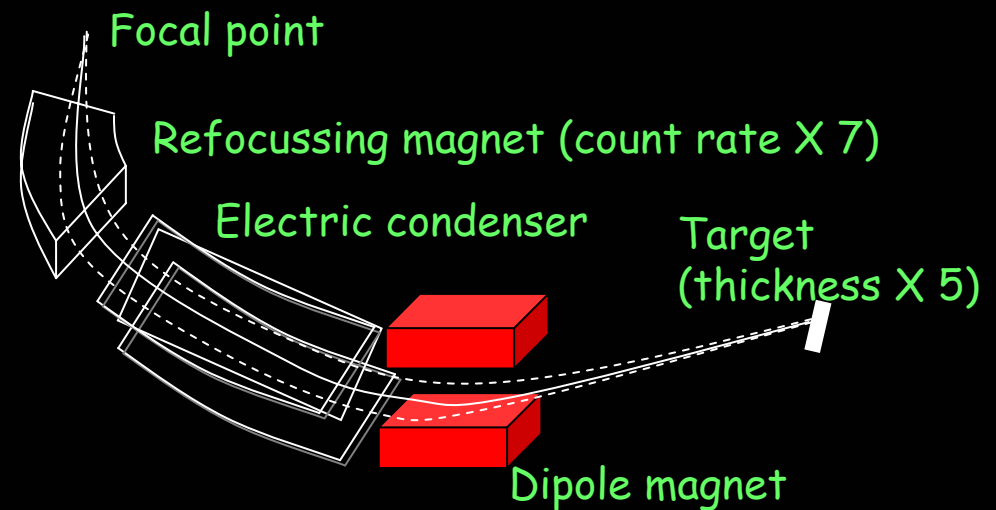
Facility : High-Flux 58.4 MW Reactor

- ☞ Neutron flux $\sim 5 \cdot 10^{14} \text{ n cm}^{-2} \text{ s}^{-1}$
- ☞ Fission rate $\sim 10^{12}$ fissions/s at target
- ☞ Fission yields depend on target (Np to Cf)

Measurement of beta spectra for $A=90, 94$:
beta singles + β - γ coincidences

- LOHENGRIN spectrometer (PN1) : A/q
- ^{235}U target (6mg) ➤ 1 HPGe clover
- 25.8mm Silicon detector

➔ test the simulation of the evolution of the beta spectrum from isobaric chains $A=90,94$



➔ Experiments at ILL, Cadarache - Saclay - Nantes over 2006 to tune the set-up

✘ Propose experiments to ALTO for the next PAC : ex : intensities of Br-Kr-Rb 100 times bigger than ILL.

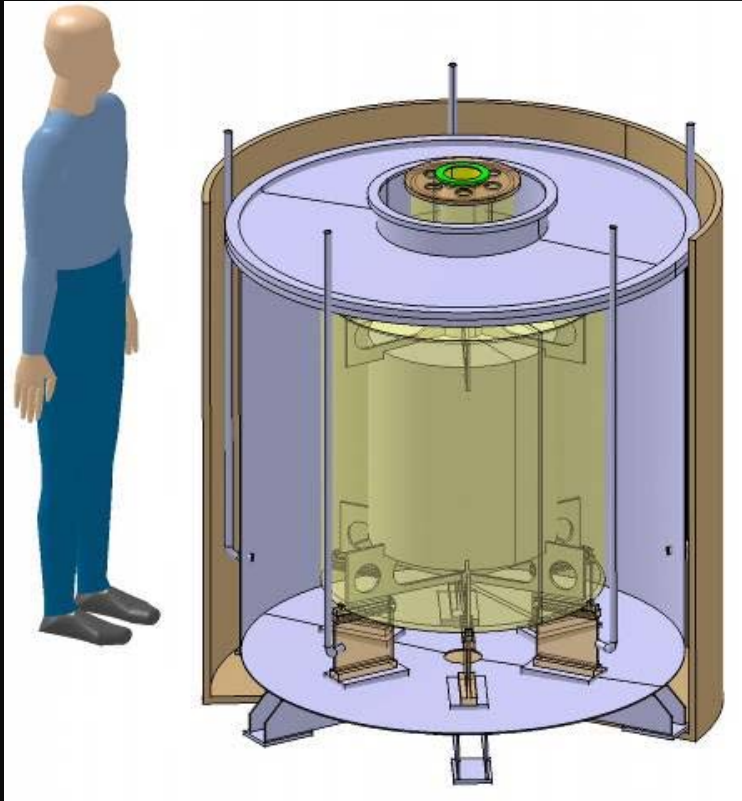
✘ Measure integral β spectrum from fast ^{238}U fission : theoretical Calculation from Vogel et al. (89), error $\leq 10\%$, gives $\leq 8\%$ of PWR reactor antineutrinos

Towards a better understanding of antineutrino spectra : n-rich fission products beta decay

- ✘ Double-chooz phase 2 : best measurement of reactor $\bar{\nu}_e$ spectrum $\sim 10^6$ evts/3y
- ✘ Double-chooz phase 1 : only far detector, better precision on the reactor $\bar{\nu}_e$ spectrum very useful !!!
- ✘ Future neutrino experiments (relic SN ...) $\bar{\nu}$ spectrum above 8 MeV never measured
- ✘ Nuclear reactors physics and safety (decay heat calc.)
/futures (Gen. IV) reactors (decay heat + β -delayed n)
- ✘ Nuclear astrophysics (r-process nucleosynthesis) ?
- ✘ Nuclear structure (exotic nuclei - shell closure problematics + β decay : forbidden transitions ?)



Outlooks : Towards a prototype of monitor for thermal power



- Test/measure at ILL : core of \approx pure ^{235}U
 - Very pure ν signal vs burn-up
 - Calibration of the ν vs thermal power
 - Simple simulation of the nuclear core
- A demonstrator to be shown at AIEA :
 - Prototype between Double Chooz approach and Sands approach (LLNL)
- An already usable tool to measure the thermal power

Project to be submitted to the Agence Nationale pour la Recherche to build and place such a detector close to the ILL high n flux reactor
M. Cribier et al.

Summary and conclusions

- **Realistic diversion (~10kg) :**
 - very small imprint on antineutrino signal
 - isotopic content in the core : present knowledge on antineutrino spectrum emitted in fission not precise enough
- **Thermal power :** - less difficult job neutrinos
 - sample the whole core without attenuation
 - valuable information with totally different systematics
 - stops or changes of power impossible to hide
- **High energy part of antineutrino spectrum :**
 - best possibility to disentangle pure ^{235}U fission from ^{239}Pu fission.
 - search for relevant observable : cumulative number of antineutrinos as a function of antineutrino energy
- **Monitoring of nuclear activities at the level of a country :** KamLAND type detector deeply submerged off the coast of the country : sensitivity to detect a new underground reactor located at several hundreds of kilometers.

