Nucifer Project: Full simulation scheme

From reactor to detector response

Jonathan Gaffiot on behalf of the Nucifer collaboration

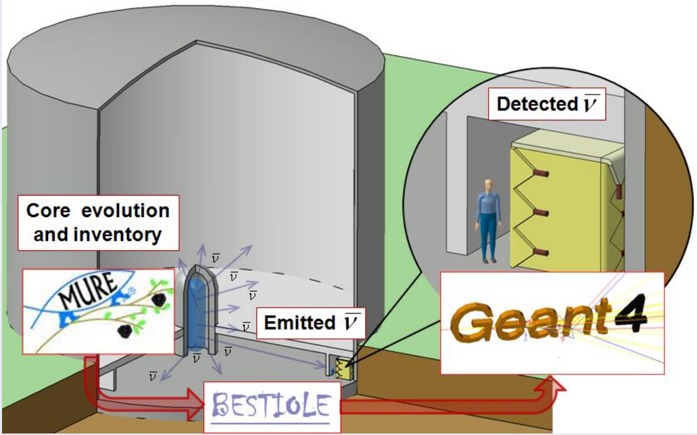
CEA/DSM/Irfu: SPhN, SPP, SEDI, SIS, SENAC
CEA/DAM/DIF/DPTA/SPN
CNRS/IN2P3: Subatech

August 3rd, 2010

Nucifer

From reactor to detector response

Goal: time prediction of detected neutrino spectra



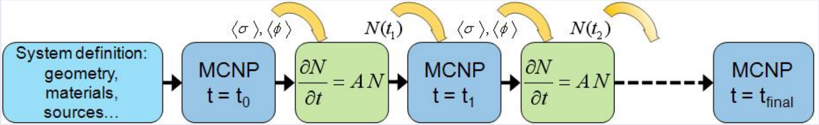
⇒ cf. T. Lasserre and R. Granelli presentations

Outlook

MCNP Utility for Reactor Evolution

Principle

- Monte Carlo: given static geometry and compositions, simulates neutron flux
- Evolution code: given a static neutron flux, simulates composition evolution
- MURE iterates these 2 simulations to get a depletion code



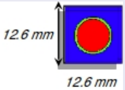
MURE: a recent open source library for reactor simulation [1]

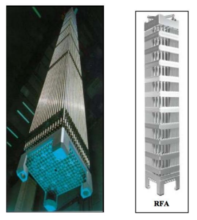
- C++ code coupled with MCNP for Monte Carlo simulation
- Developed and supported by CNRS/IN2P3: IPNO, LPSC and Subatech
- Available @ NEA data bank since 2009 (http://www.nea.fr/abs/html/nea-1845.html)
- Adapted to non proliferation needs: C++ interface for inputs description, graphical interface based on ROOT for outputs analysis, coupling with fission products β decay database, off equilibrium effect evaluation. . .

A 'N4' french PWR simulation: Inputs

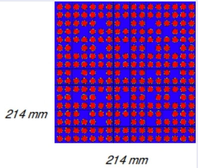
- Simulation of Double Chooz reactors: french PWR type 'N4', 4.27 GW_{th}
- Geometry, initial materials, nuclear databases, power history and time steps

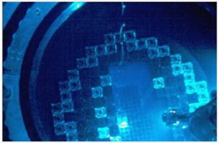
317 pellet/rod and 264 rods



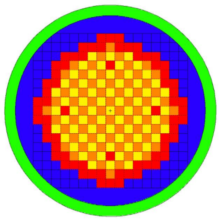


205 assemblies



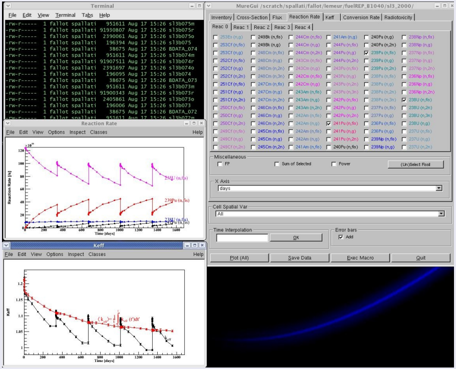


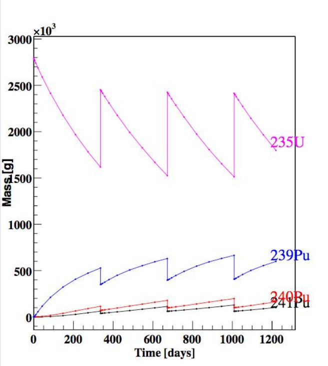
Core with different enrichment zones



A 'N4' french PWR simulation: Outputs

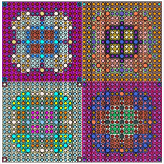
Fuel inventory, reaction rates, neutron flux, k_{eff}... at each time step



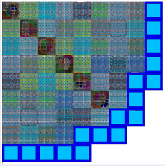


Validation and non proliferation studies

Validation



NEA benchmark:
4 Westinghouse assemblies

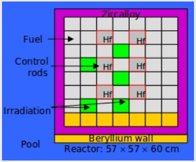


NEA benchmark:
Quarter core Westinghouse

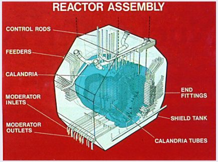
(N. Capellan PhD thesis)

- Independent NEA benchmarks and sentivity studies [1]
- Comparison with deterministic codes APOLLO2 and DRAGON

Non proliferation scenarii studies [2, 3]

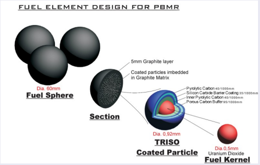


Osiris



Candu

(V. M. Bui PhD thesis)



VHTR

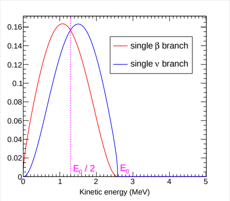
(S. Cormon PhD thesis)

Outlook

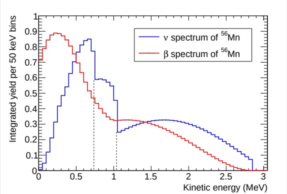
The difficulty: convert electron spectra to neutrino spectra

β decay: measurable electron energy, need to deduce neutrino energy

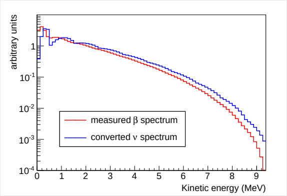
- Single β branch: direct relation between neutrino and electron energy
- Spectrum of a nucleus: superposition of many β branches
- Spectrum of a reactor: superposition of hundreds of fission products, i.e. thousands of β branches, and still unknown nuclei and branches



single β branch



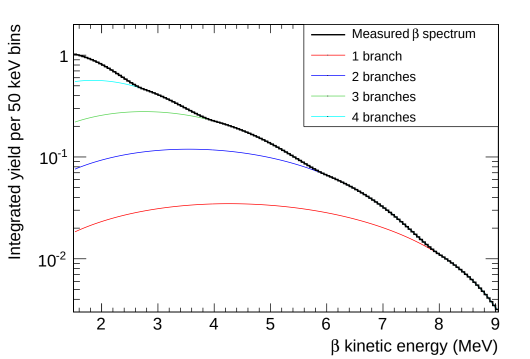
nucleus: many branches



^{235}U: hundreds of nuclei

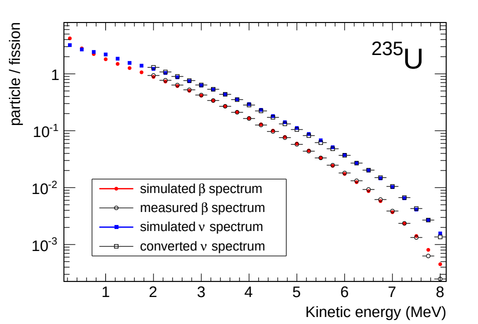
Historical approach for spectrum conversion

- e^-: accurate measurement of total spectra for each isotopes of interest
- Fit of these spectra with some tens of effective branches
- $\bar{\nu}$: converted virtual spectra from these effective branches
- Reference for all neutrino experiment: ILL e^- measurement @ 3%(1980s), and spectra conversion, see [4, 5, 6]



The microscopical approach

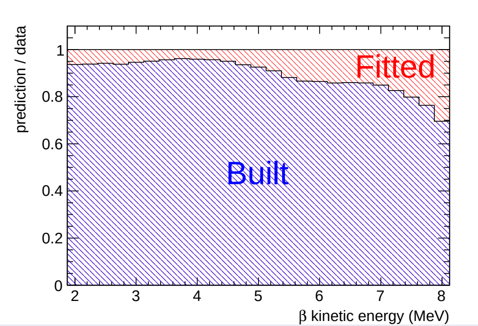
- Today in nuclear databases (JEFF, JENDL, ENDF)
  1. More than 700 fission products
  2. More than 10000 β branches
  3. Effective models for unknown nuclei
- No free parameter
- Not precise enough in norm: 5-10% with e^- data



BESTIOLE: a new code to simulate neutrino spectra

Mixing the two approaches

1. ∼ 90% of physical branches from nuclear databases
2. Match residues with effective branches
3. Reverse real and effective branches to obtain neutrino spectra

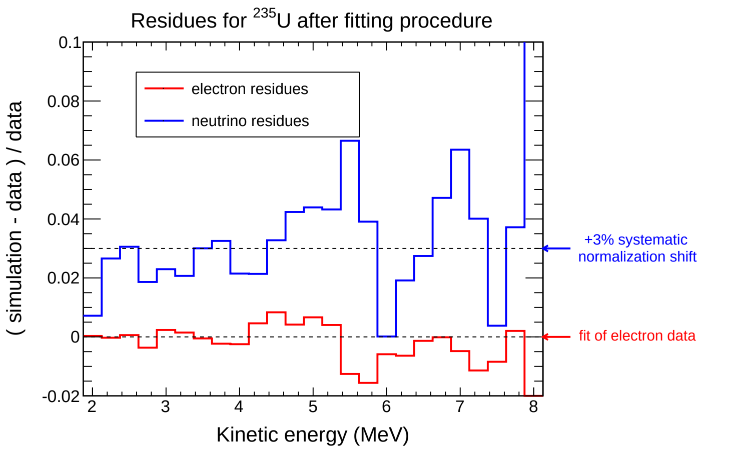


BESTIOLE: a new C++ code (Th. A. Mueller Ph.D. thesis)

- Inputs: standard nuclear databases (ENSDF format) and fission rates
- Simulate neutrino spectra for each fission product and each fissile isotopes
- Intrinsic error propagation with calculation of covariance matrix

BESTIOLE's results

Systematic 3% shift between historical and BESTIOLE spectra

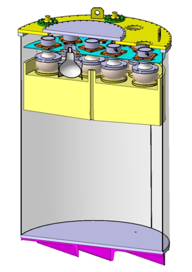


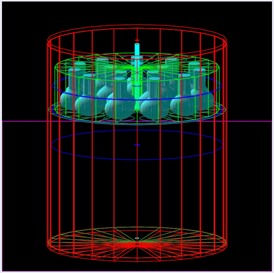
To be submitted to Phys. Rev. C.

Outlook

GEANT4 simulation of the detector

High fidelity description [7]

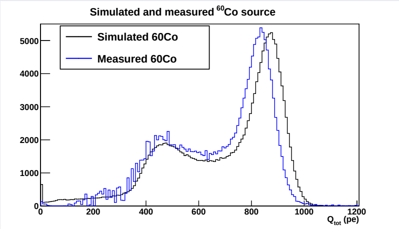


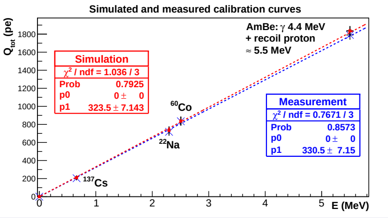


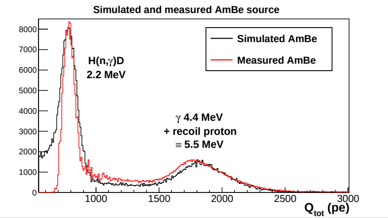
- Simulation of scintillation with dedicated model and fine liquid properties
- Multiple measurements of optical properties of detector components
- Intrinsic digitization of collected photons on simulated photomultipliers
- Output: ROOT files with the same format than experimental data
- Benefits from Double Chooz developments

Calibration: simulation and detector

Shallow depth laboratory + No shielding → Background rate of several kBq





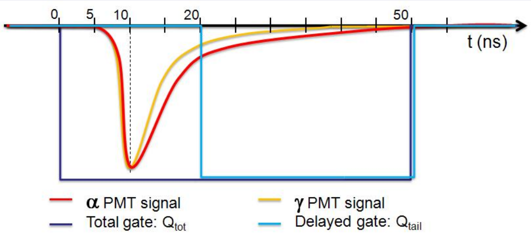


1. $^{241}_{95}\mathrm{Am} \rightarrow {}^{4}_{2}\alpha + {}^{237}_{93}\mathrm{Np}$
2. ${}^{4}_{2}\alpha + {}^{9}_{4}\mathrm{Be} \rightarrow {}^{13}_{6}\mathrm{C}^*$
3. ${}^{13}_{6}\mathrm{C}^* \rightarrow {}^{12}_{6}\mathrm{C}^* + \mathrm{n}$ (some MeV)
4. ${}^{12}_{6}\mathrm{C}^* \rightarrow {}^{12}_{6}\mathrm{C} + \gamma$ (4.4 MeV)

Fighting correlated backgrounds

Pulse Shape Discrimination

- Due to mass difference, α, p and e^- have different ionising density
- Light emission is then a bit quicker with e^- than ion
- Pulse Shape Discrimination can be used to discriminate particles

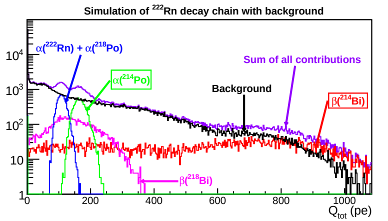


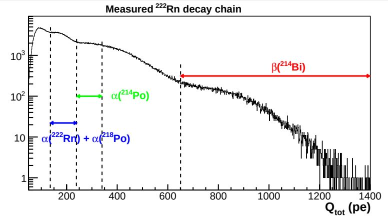
The experiment: introduction of ^{222}Rn in Nucifer

- Among ^{222}Rn daughters, ^{214}Bi decays β^- on ^{214}Po
- ^{214}Po is α emitter with half-life 164 μs
- Time correlation + 2 different particles: Bi/Po decays mimic a $\bar{\nu}$ signal

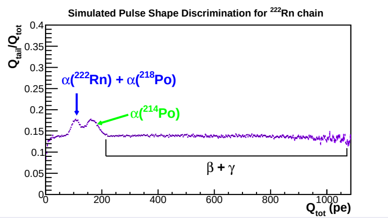
The results of the experiment

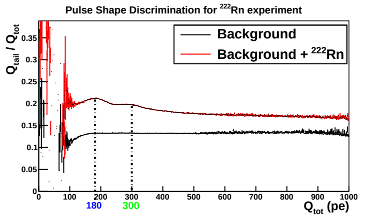
Comparison simulation/experiment





A clear indication of Pulse Shape Discrimination for α

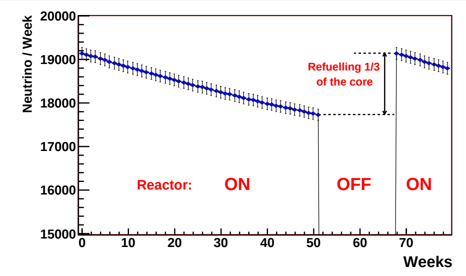


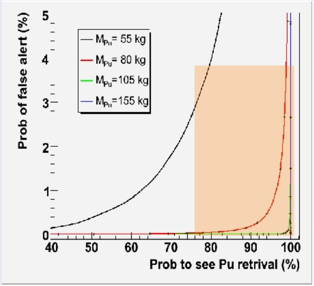


Outlook

Expected sensitivity and count rate

- At power plant: 25 m from reactor core of constant power 3.3 GW_{th}
- Detector: 0.8 m^3 of liquid with 50% efficiency
- A point with 1% statistical error each 3 days
- Sensitivity to $\sim$ 55 kg of plutonium





Conclusions and perspectives

A full simulation scheme from reactor to detector

- Inputs: Standard databases, geometrical properties and history of thermal power
- Outputs: Direct comparison with experimental data
- Many new developements: evolutionnary Monte-Carlo for reactor simulation, improvement of $\bar{\nu}$ spectra, detector simulated from scintillation to digitization
- Non proliferation scenario studies with Nucifer on power and research reactors

Perspectives

- Comparison of Osiris $\bar{\nu}$ spectra simulation with data
- Fine tuning of GEANT4 simulation on final detector
- Accurate non proliferation studies with final Nucifer performances

Back-up slides

References

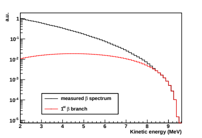
- O. Méplan *et al.*, MCNP Utility for Reactor Evolution - Description of the methods, first applications and results, *Proc. ENC*, 2005
- M. Fallot *et al.* "Nuclear reactor simulations for unveiling diversion scenarios: capabilities of the antineutrino probe," *Proc. GLOBAL*, 2009
- F. Yermia *et al.* "The Nucifer experiment: antineutrino detection for reactor monitoring," *Proc. GLOBAL*, 2009
- F. Von Feilitzsch, A. A. Hahn and K. Schreckenbach, "Experimental Beta Spectra From Pu-239 And U-235 Thermal Neutron Fission Products And Their Correlated Anti-Neutrinos Spectra," *Phys. Lett.* B **118** (1982) 162.
- K. Schreckenbach *et al.*, "Determination Of The Anti-Neutrino Spectrum From U-235 Thermal Neutron Fission Products Up To 9.5-Mev," Phys. Lett. B **160** (1985) 325.
- A. A. Hahn *et al.*, "Anti-Neutrino Spectra From Pu-241 And Pu-239 Thermal Neutron Fission Products," Phys. Lett. B **218** (1989) 365.
- A. Porta. "Reactor neutrino detection for non proliferation with the Nucifer experiment," *Proc. TAUP*, 2009, and *J. Phys. Conf. Ser.*, 203, 2010

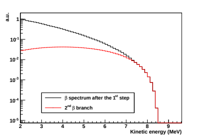
See also

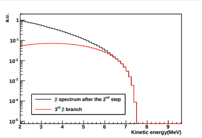
- MURE: http://lpsc.in2p3.fr/gpr/MURE/html/MURE/MURE.html
- MURE @ NEA: http://www.nea.fr/abs/html/nea-1845.html
- BESTIOLE: Th. A. Mueller Ph.D. thesis
- GEANT4: http://geant4.cern.ch/
- ROOT: http://root.cern.ch/drupal/
- D. Lhuillier *et al.* The Nucifer experiment: reactor monitoring with antineutrinos for non proliferation purpose. *Proc. GLOBAL*, 2009
- A. Porta *et al.* Reactor neutrino detection for non proliferation with the NUCIFER experiment. *Proc. ANIMMA*, 2009 IEEE 10.1109/ANIMMA.2009.5503653
- L. Giot *et al. Proc. PHYSOR*, 2008
- M. Fallot *et al. Proc. Nuclear Data, B.*, 2007
- B. Guillon *et al. Proc. GLOBAL*, 2007

Conversion procedure

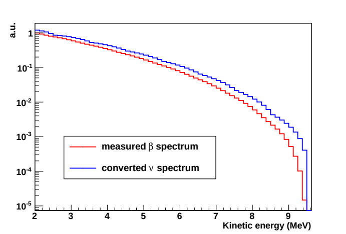
1. Fit of the measured spectrum's tail with an effective branch
2. Substraction of the branch
3. Iteration $\sim$ 30 times





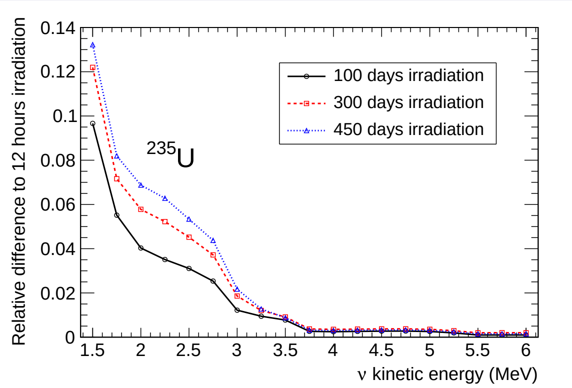


- Individual conversion of each branch with energy conservation
- Sum of all of them to get the total spectrum



Main corrections brought by MURE

- Out equilibrium spectra: long-lived fission products
- Neutron capture on fission products
- Shape of neutron flux (axial offset, pilot rods. . .)



Noise simulations

Noise measurement with HPGe as input to simulation