Nuclear Reactor & β/ν Spectra Simulations for reactor antineutrino applied physics, links with TAGS measurements

- SUBATECH team : V.M. Bui, M. Fallot, L. Giot, J. Martino and F. Yermia
  S. Bouvier, H. Carduner, G. Guilloux, C. Renard and D. Roy

UNIVERSITÉ DE NANTES
ECOLE DES MINES DE NANTES
CNRS
IN2P3
Subatech

GEDEPEON
GROUPEMENT DE RECHERCHE
CEA - CNRS – EDF - FRAMATOME

Outline

- Double Chooz neutrino oscillation exp. : state of the art for reactor antineutrinos detection

- Dedicated detector developments and experiments : miniature antineutrino detector for reactor monitoring : Songs1, Nucifer, Angra, Kaska… : expected sensitivity

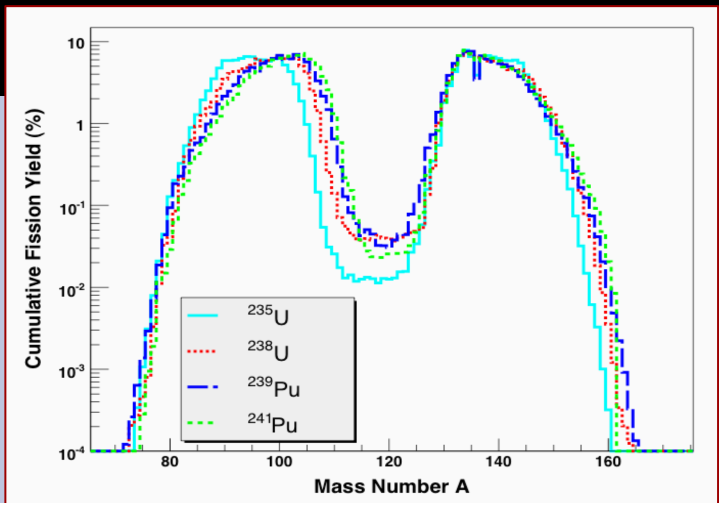
- Selected associated Reactor and antineutrino spectra simulation activities, nuclear databases comparisons

- *Links with "Better evaluation and prediction of reactor decay heat"*

- *Outlooks : Experimental nuclear physics : study of beta and gamma decay properties of fission products (for reactor decay heat, antineutrino spectra, and astrophysics).* (contacts with J.L. Tain and A. Algora)

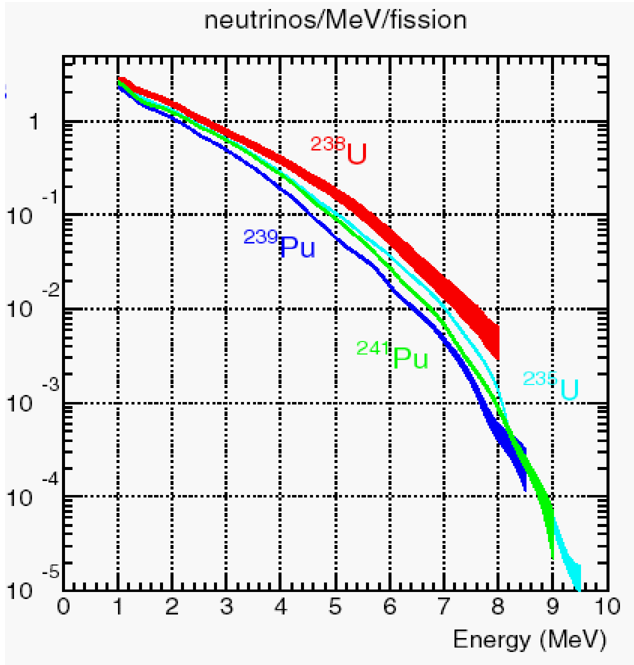
Where do antineutrinos from reactors come from ?

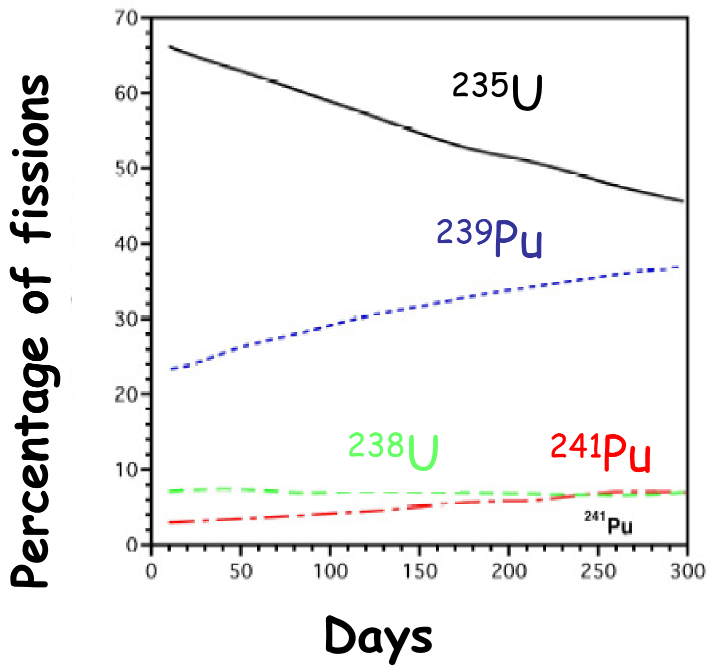
	^{235}U	^{239}Pu	^{238}U	^{241}Pu
E_f (MeV)	201.7	210.0	205.0	212.4
$\langle E_\nu \rangle$ (MeV)	1.46	1.32	1.56	1.44
$\langle N_\nu \rangle$ (E>1.8MeV)	5.58 (1.92)	5.09 (1.45)	6.69 (2.38)	5.89 (1.83)



- The fission products are neutron-rich nuclei

↳ β^- decay : $\quad {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^- + \overline{\nu}_e$





Antineutrinos from reactors

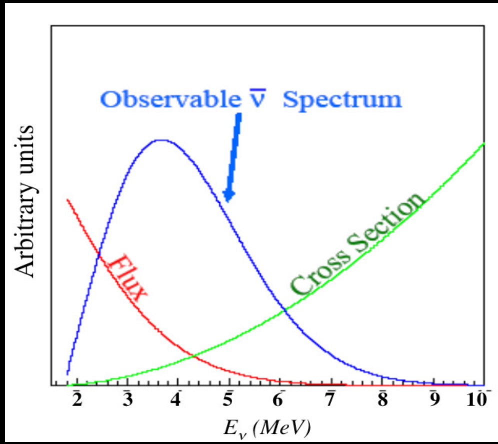
- Standard power plant 900 MW_e : $\frac{2800\ \mathrm{MW_{th}}}{200\ \mathrm{MeV}} \times 6\ \overline{\nu}_e$ $\sim 5 \cdot 10^{20}\ \overline{\nu}_e / s$

- Detection through inverse β-decay process on quasi-free proton :

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

✓ Reaction threshold : 1.8 *MeV*

✓ Interaction cross-Section *(α E_ν^2)* : $<\sigma> \sim 10^{-43} cm^{-2}$



*[C. Bemporad et al,. Rev. of Mod. Phys., **74** (2002)}*

➡ Correlation antineutrino flux vs thermal power

- $N(E_{\bar\nu})\ \alpha\ \left(1 + k_{(E_{\bar\nu})}\right) W_{th}$

Fuel composition, energy spectrum — thermal power

- For a fixed fuel composition ***(k=cste)***, the ν_e flux is directly proportionnal to the thermal power.
- For a constant thermal power ***(Wth=cste)***, the ν_e flux as well as the ν_e energy spectra depend on the fuel composition.

*[Klimov, Kopeikin, Mikaelian et al. At. Ener. **76** 2(1994) 123-127]*

The antineutrino probe

On-going international projects : USA, France, Brazil, Japan, Russia

SUBATECH collaborations :

CEA/IRFU, CEA/DAM, CNRS/IN2P3/IPN Orsay, CNRS/IN2P3/LPSC Grenoble, CNRS/IN2P3/APC

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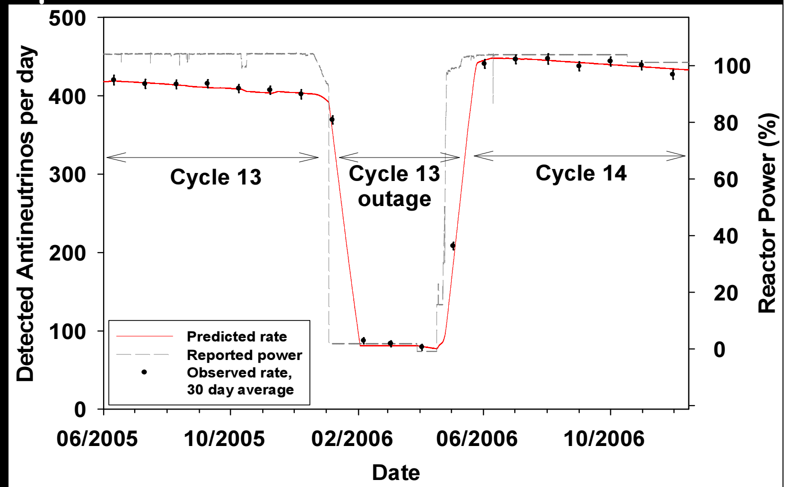
International Double Chooz collaboration : France, US, Brazil, Germany, Japan, Spain, Russia



N. Bowden et al., NIMA 572 (2007) 985

IAEA interest :

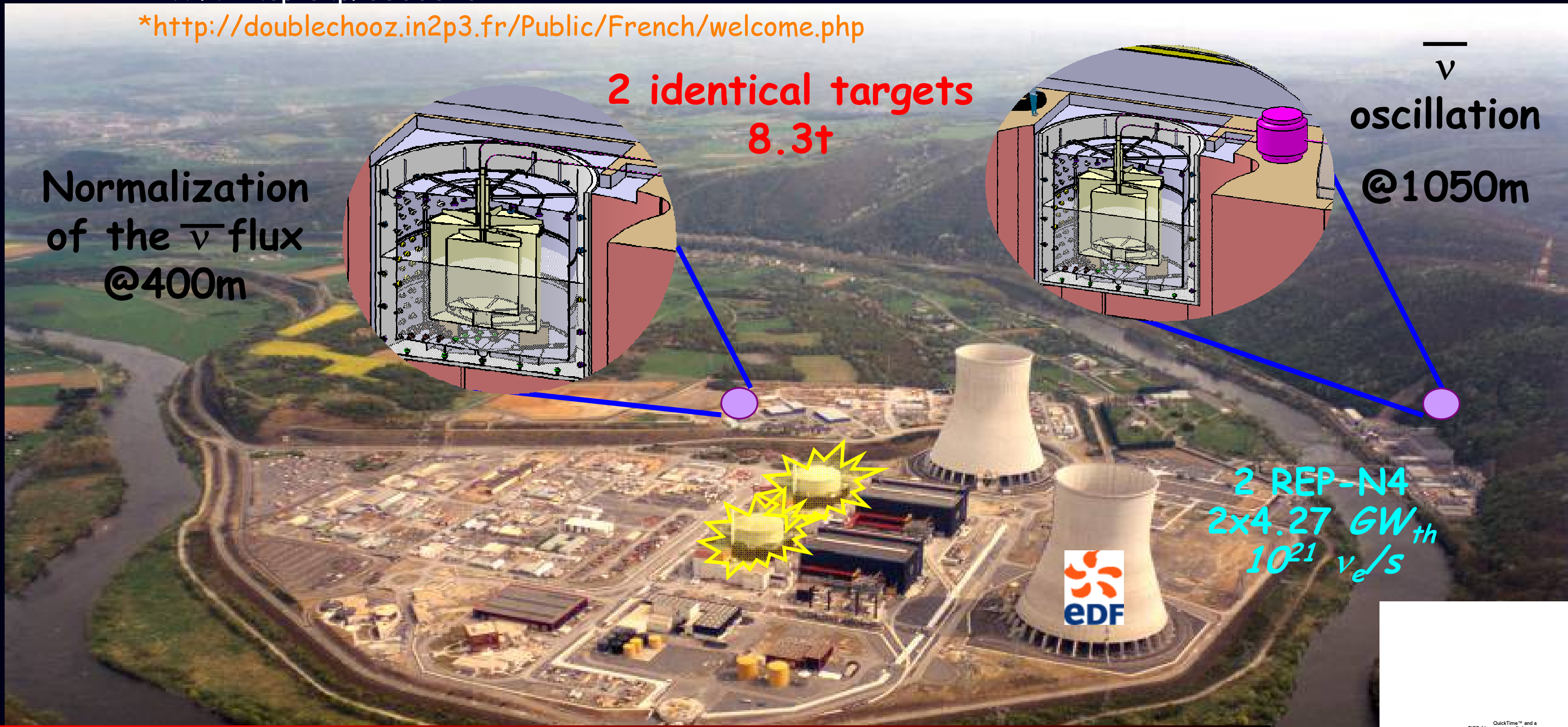
IAEA.org International Atomic Energy Agency

International expert meeting organized by the New Technologies Department from IAEA October 26-28. 2008

IAEA may be interested by an antineutrino detector concept, in particular for future reactors (ex. PBMR, Gen IV…, safeguards by design)

Double Chooz Experiment*

*ArXiv : hep-exp/0606025
*http://doublechooz.in2p3.fr/Public/French/welcome.php

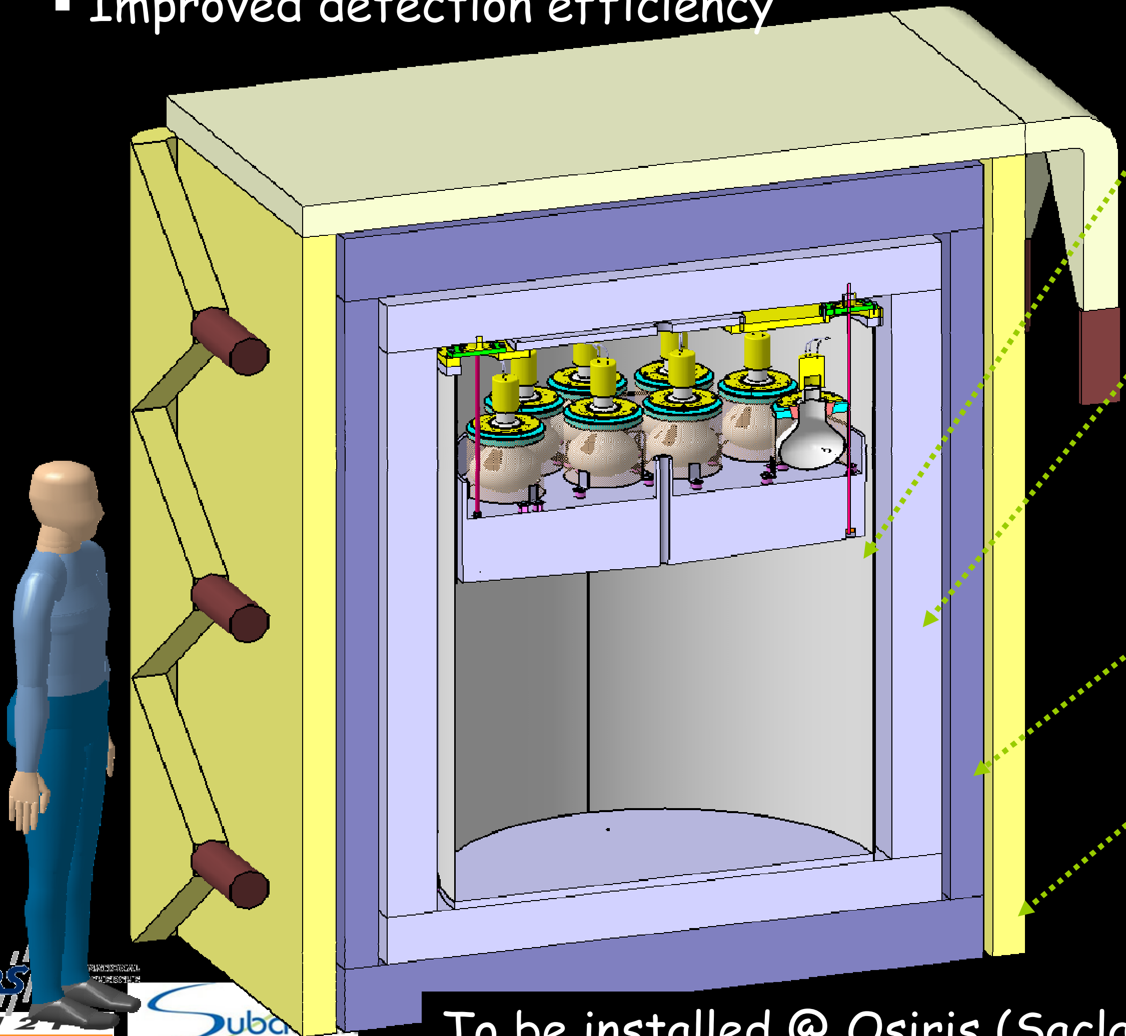


- <u>SUBATECH implications</u> : nuclear physics and non proliferation

- Applications of antineutrinos : thermal power measurement and new safeguards tool ?
- **Double Chooz phase 1** : when far detector only : need of a better and precise determination of the ν_e spectrum => absolute normalisation of first measurements !!!
- **Double Chooz phase 2** : best measurement ever done of the antineutrino spectrum : determine the sensitivity limit of the antineutrino probe

Nucifer Detector Concept

- Detector design: a simple monolitic detector with PMTs on the Top
  - Small, Safe, Robust
  - Remotely operable
  - Rate + energy spectrum
  - Improved detection efficiency



- Target: ~1 - 1.5 m^3 Gadolinium loaded liquid scintillator
- Steel vessel + reflective Coating Inside to wash non uniformities – box geometry for final detector to maximize the volume
- 10 cm Low-Z Shielding for Gammas
- 15 cm High-Z Shielding for neutrons
- Muon Veto (plastic scintillator)

To be installed @ Osiris (Saclay) and HFR (Grenoble) in 2010

ν-spectra determinations

- **Integral β-spectra measurements:** *[A. Hahn et al., Phys. Lett. B, 218, (1989)]*
  - ✓ ^{235}U, $^{239,241}Pu$ *targets* @ILL, at better than 2% until 8 *MeV*

- Conversion $\beta^- \rightarrow \nu_e$: global shape uncertainty from 1.3%@3MeV to 9%@8MeV
- Measurement only related to thermal fission
- Irradiation time dependence *(20 min & 1.5 d)*

- **Summing individual β-spectra:** *[Tengblad et al. (NPA503(1989)136) 111 nuclei @OSIRIS Studsvik and ISOLDE]*

- Don't agree with the experimental integral spectra (important errors : 5% at 4MeV, 11% at 5MeV and 20% at 8MeV)

- Remaining short-lived, high Q_β, unknown nuclei

Principle of our strategy

$$N_{\bar{\nu}}(E_{\bar{\nu}},t) = \sum_n \underbrace{Y_n(Z,A,t)}\cdot\underbrace{S_{\bar{\nu},n}(Z,A,E_{\bar{\nu}})}$$

fissile mat. + FY

neutron flux

Core geometry

Monte-Carlo Simulation : Evolution Code MURE

β^- decay rates $Y_i(Z,A,t)$

Two distinct studies

xp. spectru

nuclear database

models

β-branch database : BESTIOLE, …

β^-/ν_e spectra $S_{\bar{\nu},i}(Z,A,E_{\bar{\nu}})$

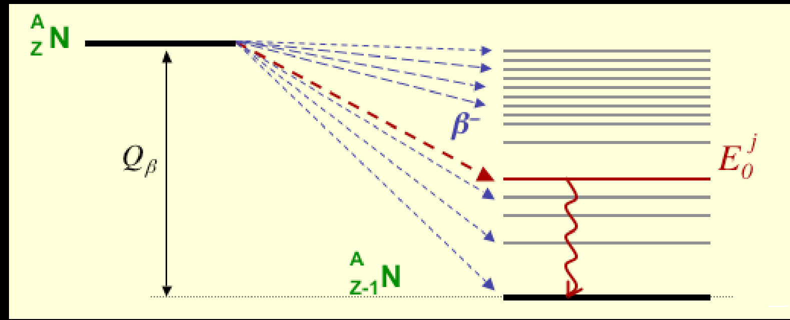
weighted Σ

Total ν_e and β^- energy spectra with complete error treatment

The ν_e spectra formulation

$$S_{\bar{\nu},n}(Z,A,E_\nu) = \sum_i b_{n,i}(E_0^i)\ P(E_0^i, E_\nu)$$

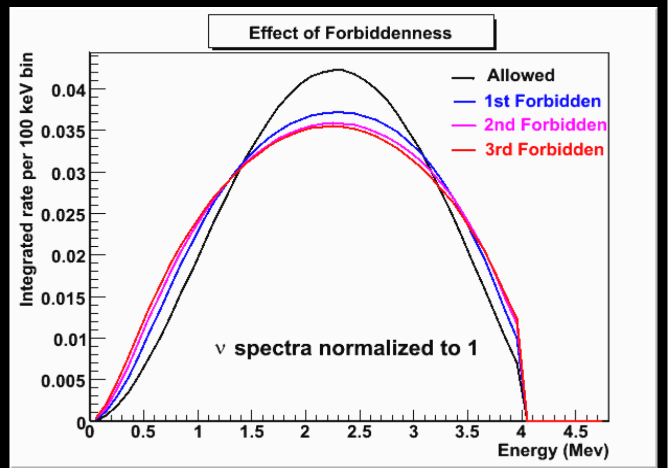
branching ratios — β individual spectra



depends on the β transition : Branching Ratios, End-Points, spin, parity of the mother and daughter nuclei

with $$P(E_0^i, E_{\bar{\nu}}) = F(Z,E)\cdot pE(E_0^i - E)^2 \cdot S_\nu(E)$$

- Coulomb corrections
- Phase space
- Spectral Shape factor *(Well controlled for allowed and forbidden unique transitions)*

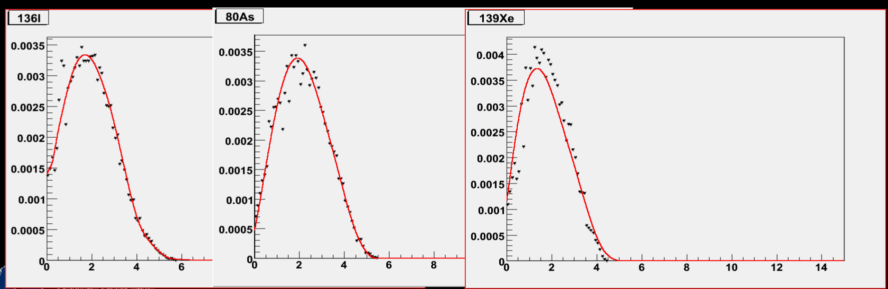


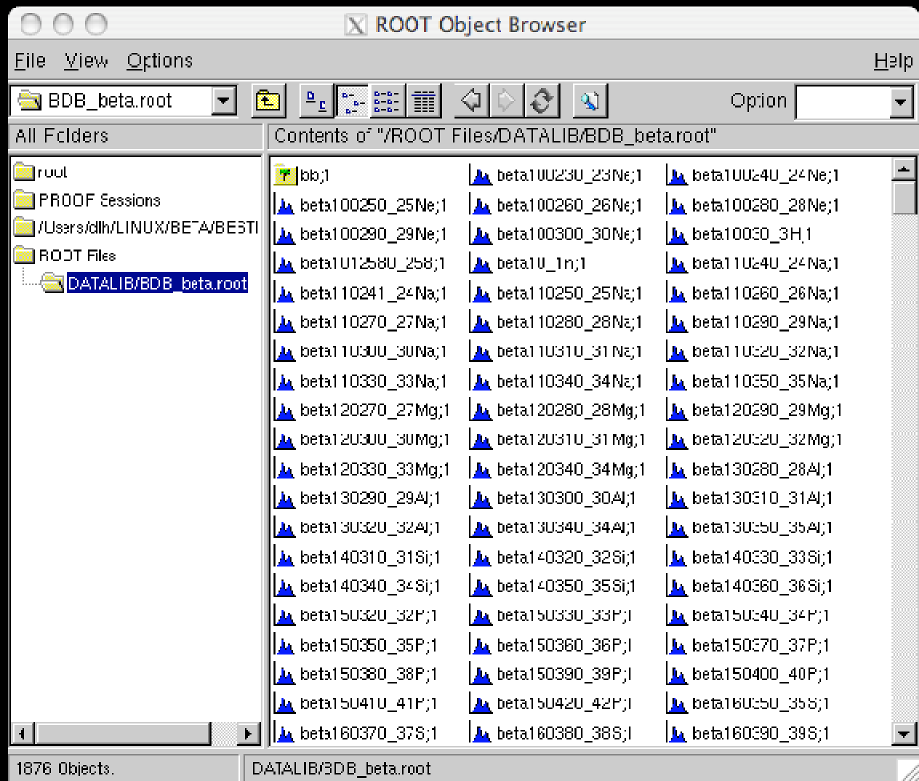
Remaining short-lived, high Q_β, unknown nuclei

Bestiole Database

- Collect all available information :
  - ✓ Nuclear Database : ENSDF
  - ✓ Experimental spectra
    - *111 nuclei @ISOLDE [O. Tengblad et al., Nucl. Phys. A, **503**, (1989)]*

- 950 nuclei :
  - ✓ ~ 10000 β branches
  - ✓ ~ 500 β-n branches
- Tag all relevant information :
  - ✓ Forbiddenness (spin & parity)
  - ✓ Level of approximation



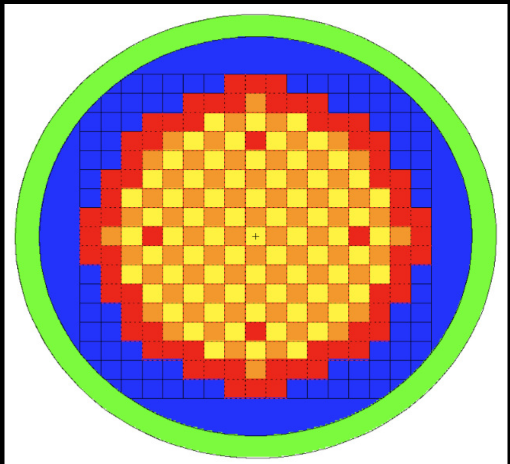


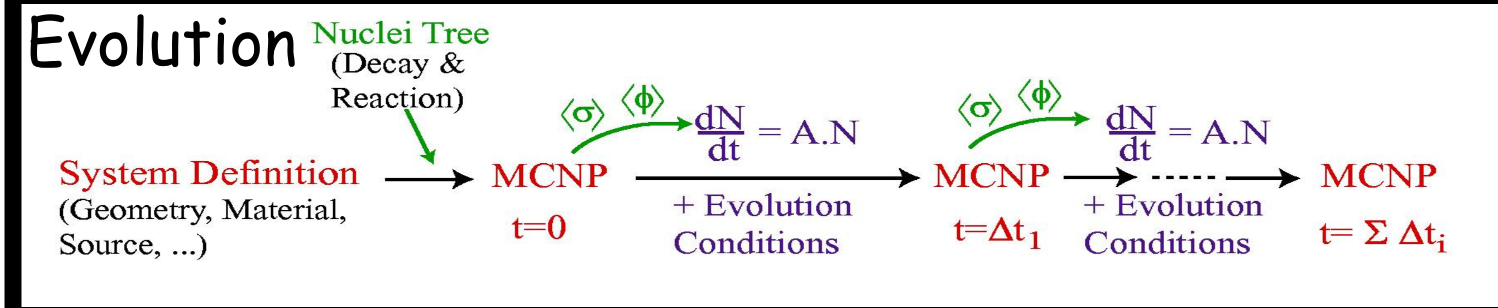
M. Fallot et al., I And CEA/Saclay/SphN : D. Lhuillier, Th. Müller et al.

MURE *

*MCNP Utility for Reactor Evolution, O. Méplan et al. ENC Proceedings (2005)
Developed by CNRS/IN2P3/IPNO and LPSC

Geometry





- Open source code : adapted to antineutrino needs (simple geometry implementation, easy coupling to databases ...) ✓
- Benchmarked with APOLLO2 code ✓
- Fuel Burnup ✓
- Fission product distributions ✓
- Refined effects : out of equilibrium spectra ✓
- n capture on FPs ✓

...

Possibility to simulate :

- Simple cases : pure U or Pu isotope fissions and associated β/ν spectra
- Complexe cases : reactor and associated β/ν spectra

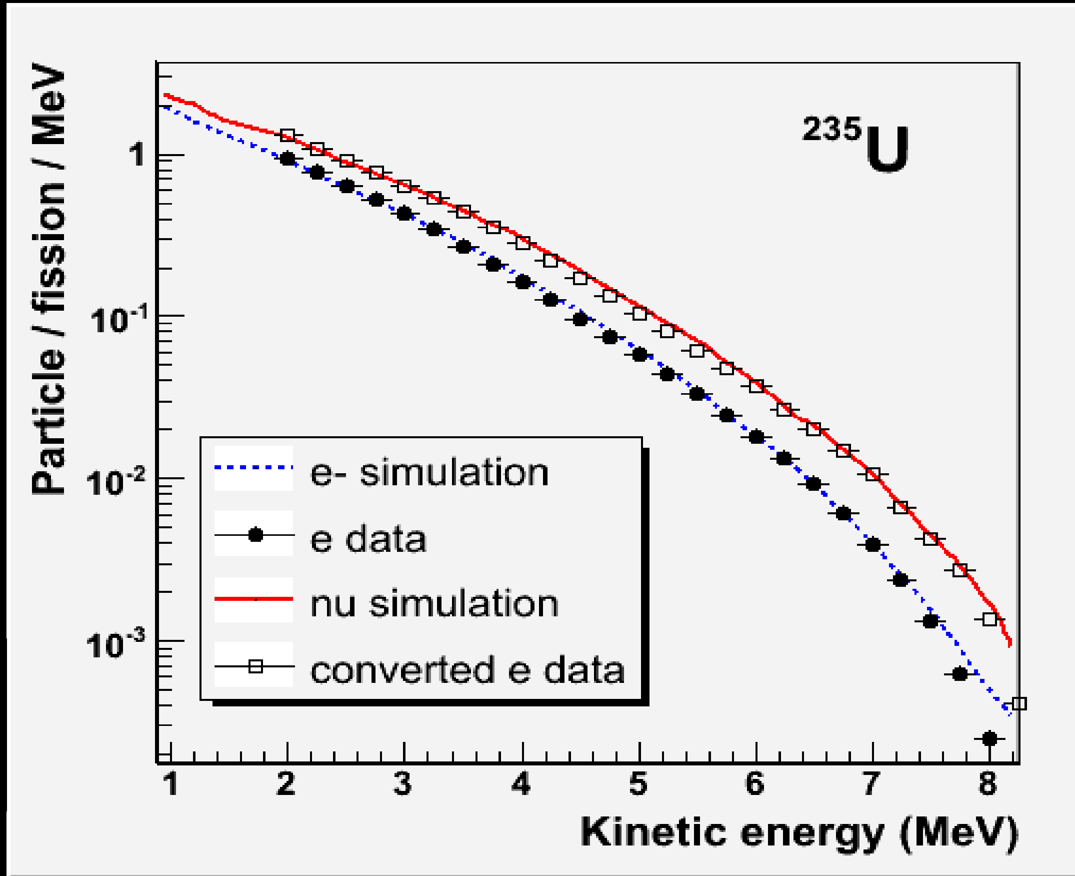
⇒ applicable to decay heat calculations

Obtained spectra

- Control of errors

- Expected improved accuracy on final spectrum shape (<2% in relevant energy range).

∏ Software tool for all kind of sensibility studies



To go further :

Several problems to solve to get a better agreement on Schreckenbach's beta data

- Unknown nuclei

- Partially known nuclei : Pandemonium effect

Several tracks to solve these problems :

- Use of Gross Theory in existing databases such as JENDL3.3 when the considered nuclei have been treated

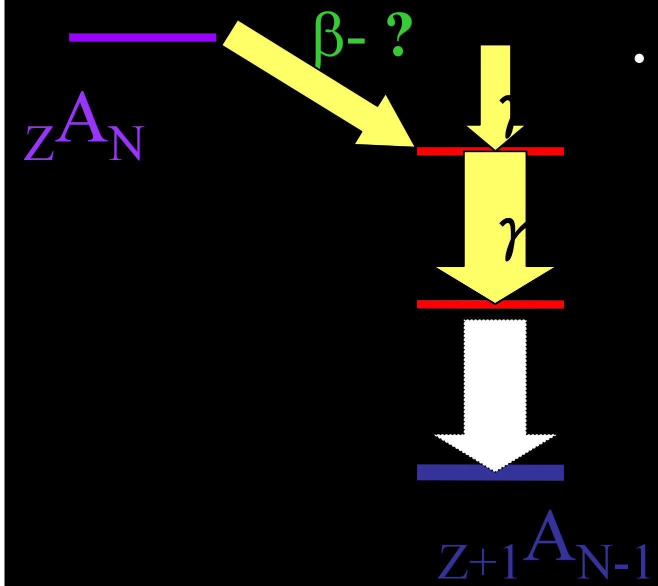
- Sensitivity to fission yields databases

-Other models : microscopical models (QRPA), « home-made » phenomenological models (Davis, Vogel et al. PRC19(1979)6) ?

- Inclusion of existing TAGS nuclear data and new measurements ?

Pandemonium effect

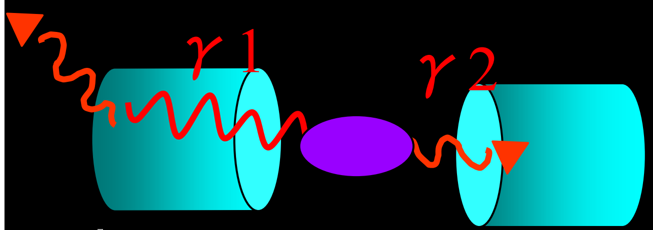
The problem of measuring the β - feeding (if no delayed part.emission)



- use of Ge detectors to construct the decay scheme
- From the γ-balance : extract the β -feeding

Low efficiency of Ge detectors at high energy
+ loss of low energy gamma rays from complex decays
=> Pandemonium effect = displacement of the β- strength (overestimation of high energies)

Hardy et al. Phys. Lett. B 1977



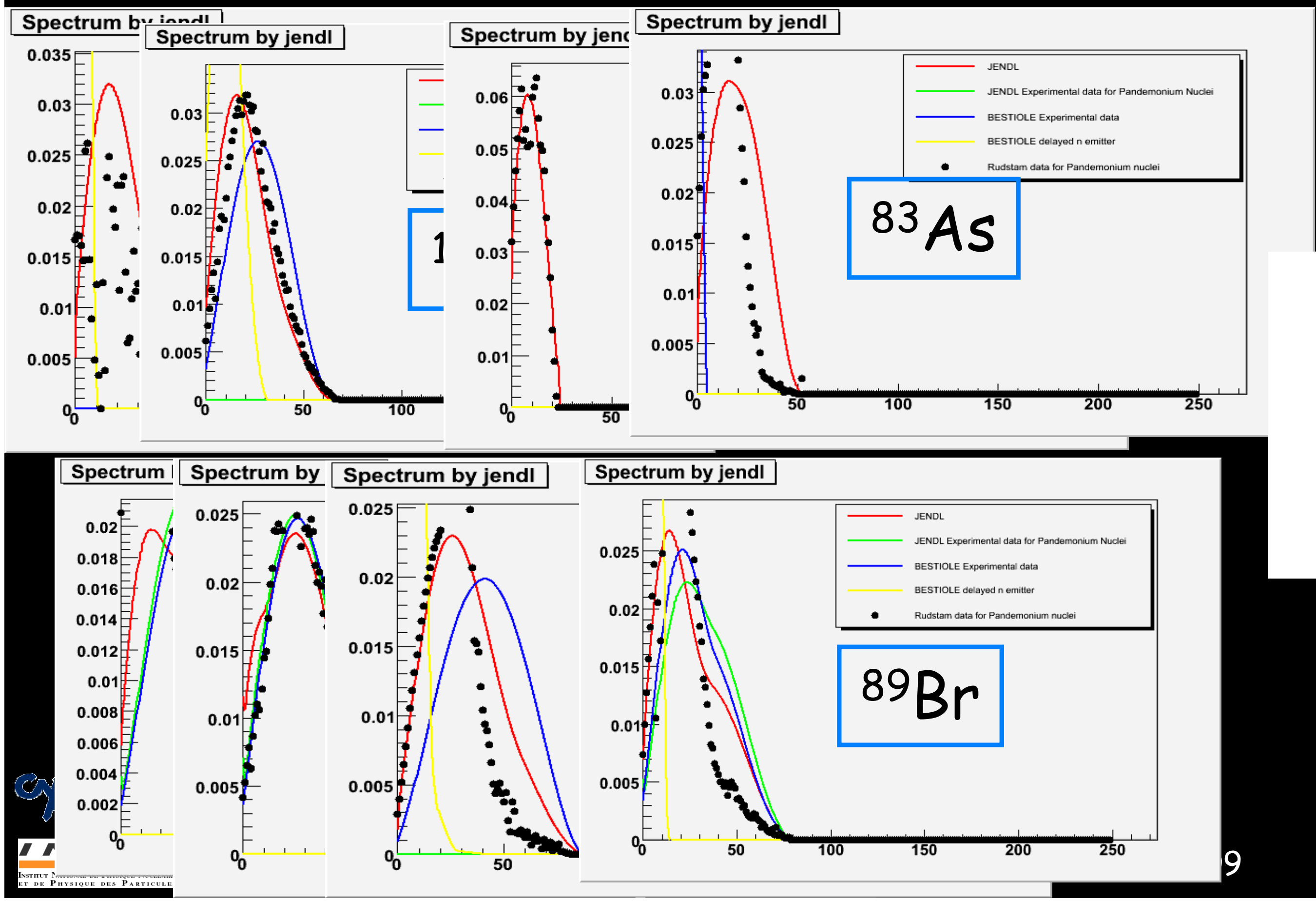
« Pandemonium effect » = indication to explain the remaining discrepancy between our simulation and Schreckenbach ?

Comparison of nuclear databases and Rudstam's data

Ex. : Gross Theory in JENDL 3.3 : - Full Gross Theory spectrum for unknown nucleus
- Partial Gross Theory spectrum for nucleus considered to be incomplete (Pandemonium) (around 100 such nuclei)

In JENDL's database : a nucleus is tagged « Pandemonium » when the maximum level energy quoted in the ENSDF data is much lower than its Q_β

Weight between estimated spectra and experimental data adjusted to reproduce the average beta energy value

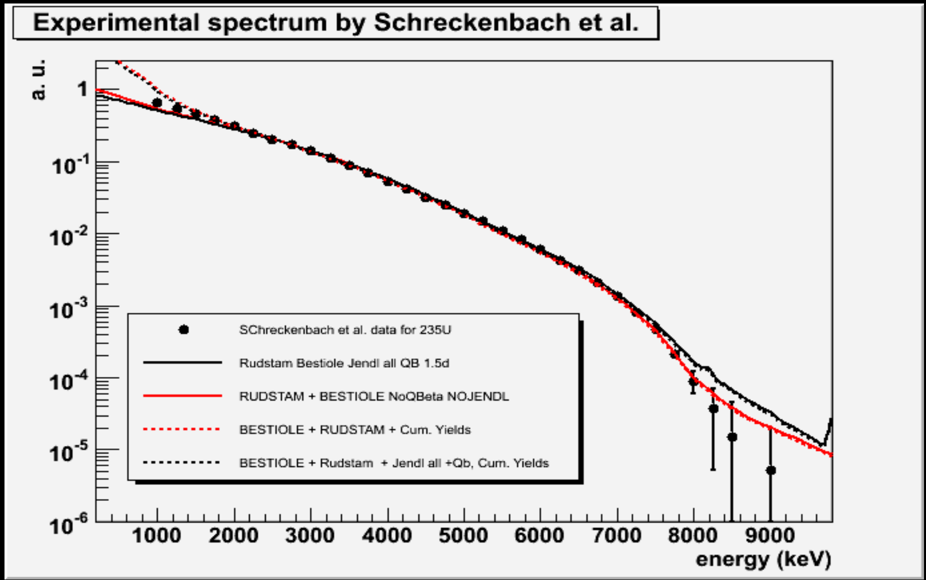


● Rudstam et al. data
JENDL total
JENDL exp. (ENSDF)
BESTIOLE exp. (ENSDF)
BESTIOLE beta-n branches (ENSDF)

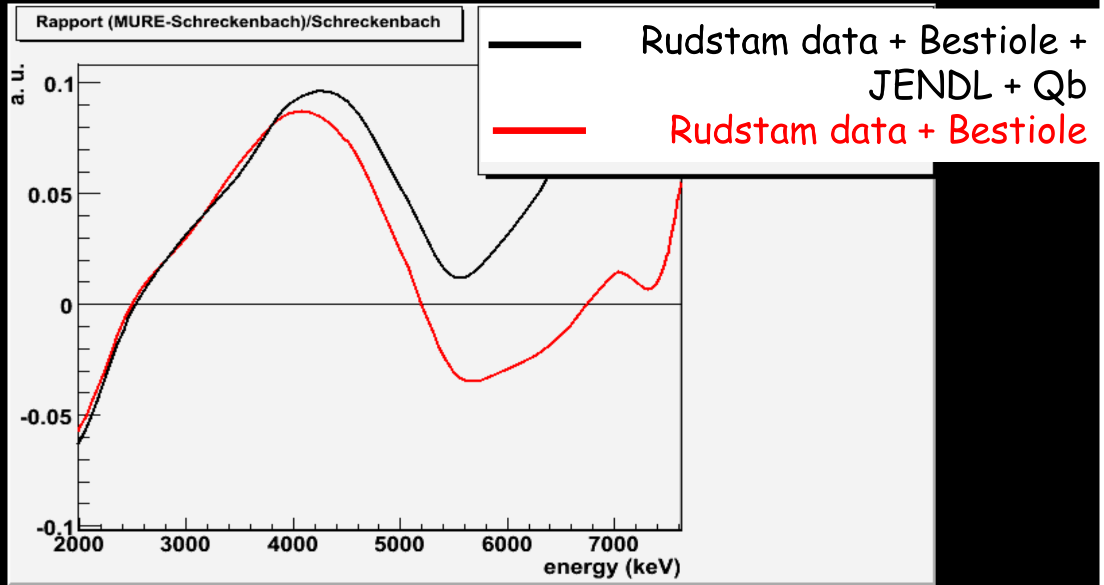
Preliminary

New ^{235}U spectrum with : Rudstam data + BESTIOLE + JENDL + QBeta

MURE evolution for 1.5d   Yields from ENDF



Ratio : (MURE - DATA)/DATA



Beta spectrum using Rudstam's data and Bestiole : a lot of missing nuclei
=> Underestimation from 4-MeV
Compared with the case where the remaining nuclei are taken from JENDL :
=> Partial compensation

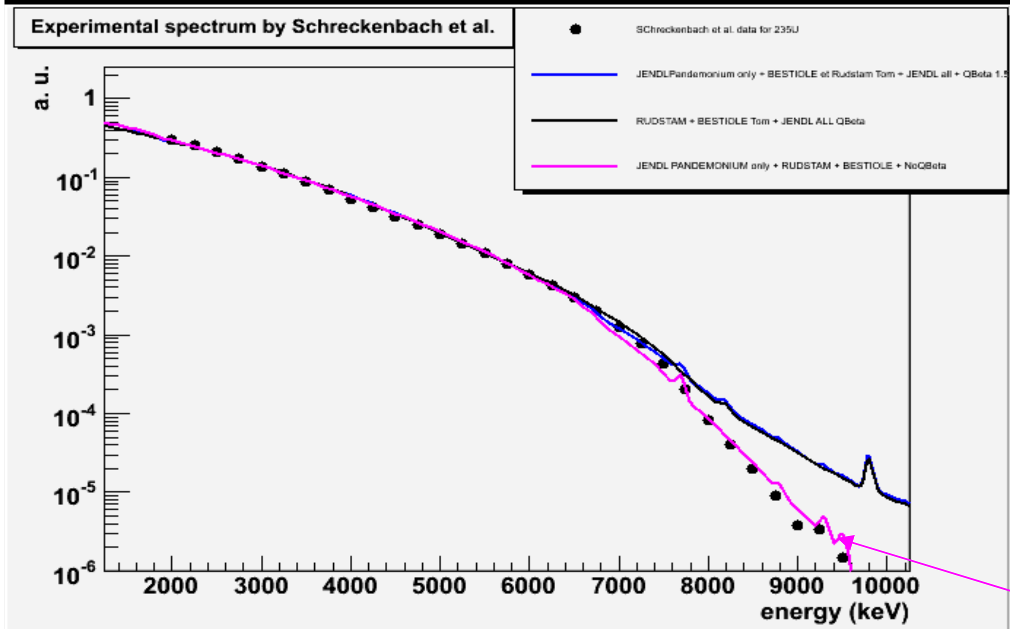
« Qbeta » approx. : when no data, assume decay from ground state to ground state
Still Qbeta nuclei : contributions between 0.5 to 2% beyond 4.5MeV

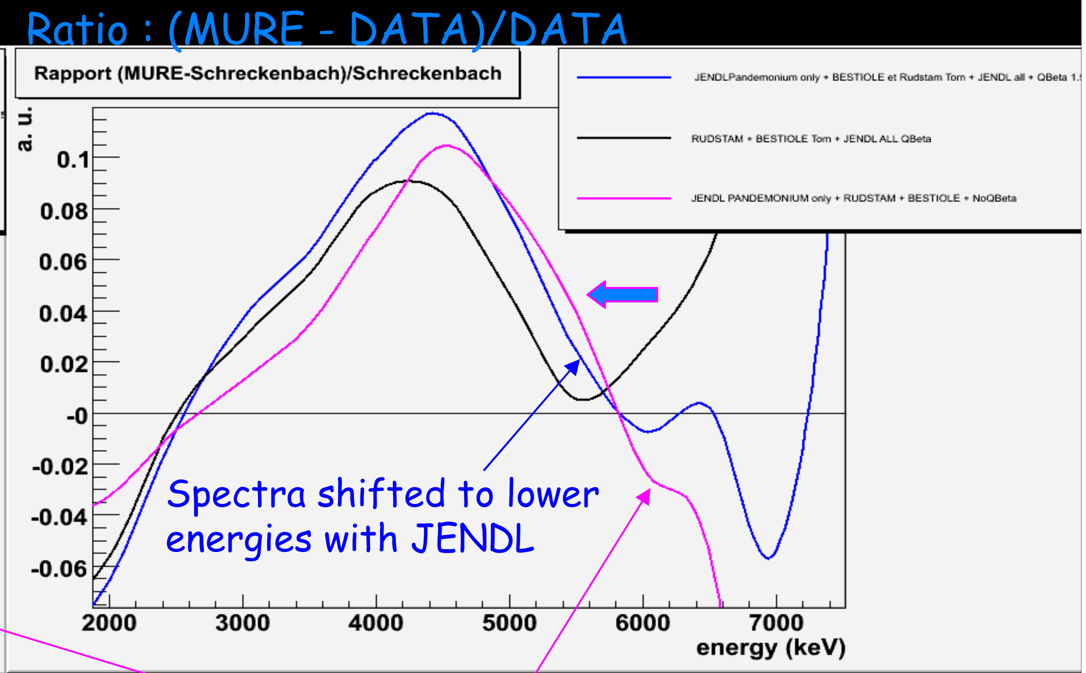
New ^{235}U spectrum with :

Preliminary

Replacements of Rudstam and BESTIOLE spectra by JENDL :

- ● Schreckenbach et al. data
- (blue line) JENDL Pandemonium tagged nuclei + Rudstam + Bestiole + JENDL rest of the db + Qb
- (black line) Rudstam data + BESTIOLE + all JENDL + Qb
- (magenta line) JENDL Pandemonium tagged nuclei + Rudstam + Bestiole





Case where remaining nuclei are dropped

Yields from ENDF

Preliminary

^{235}U

For a given prescription of the beta decay databases :

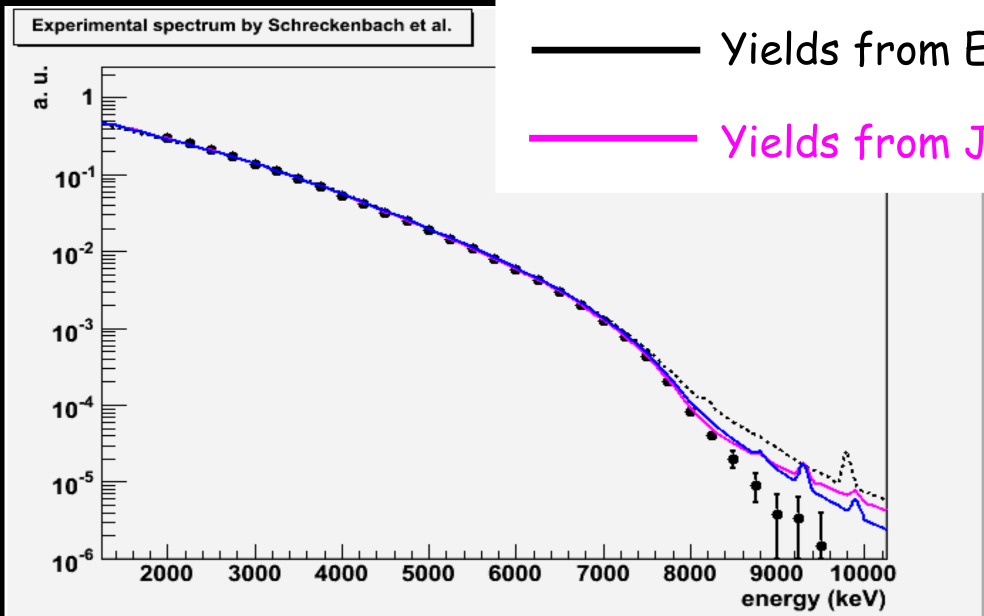
Different databases for fission yields : important input of our calculations with MURE or at equilibrium with cumalative yields

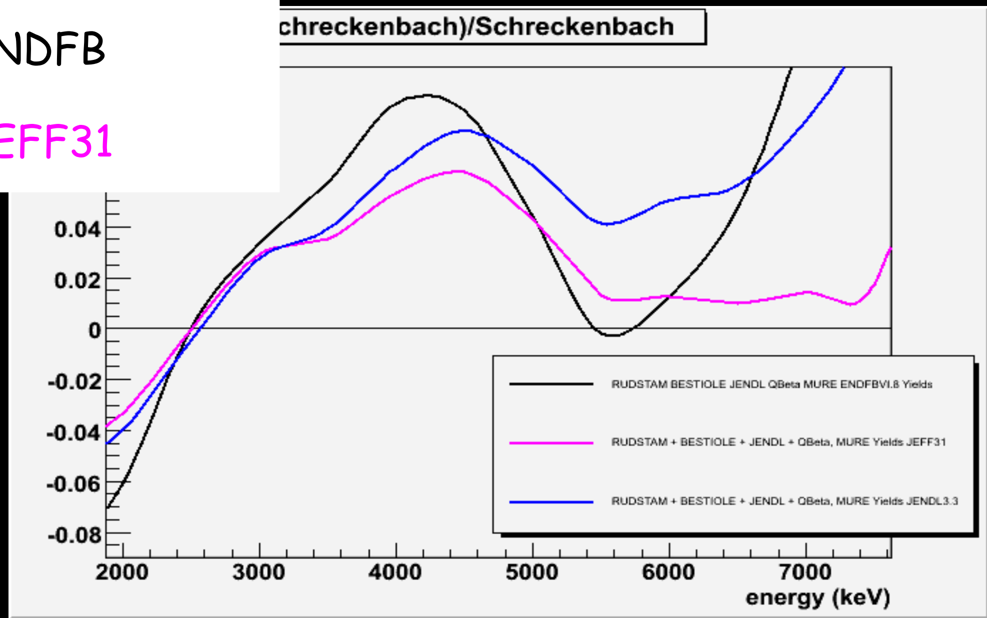
Yields from JENDL3.3

Yields from ENDFB

Yields from JEFF31

Ratio : (MURE - DATA)/DATA



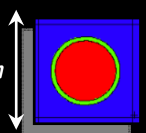


M. Fallot et al., IAEA TAGS meeting, Jan. 27. 2009

PWR N4 : Chooz-B (I, II)-like reactor

Fuel element

- 317 pellets / h =
- Zircaloy coating
- 3 Enrichments :
  (1.8, 2.4, 3.1 %.)



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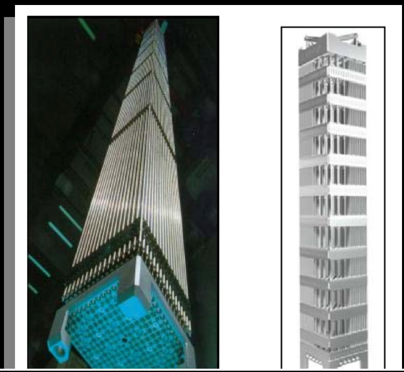
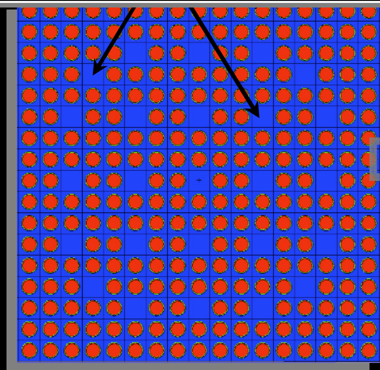
Assembly





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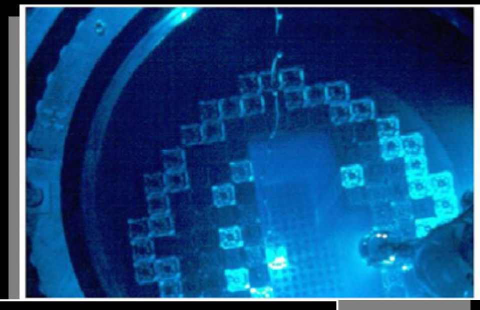
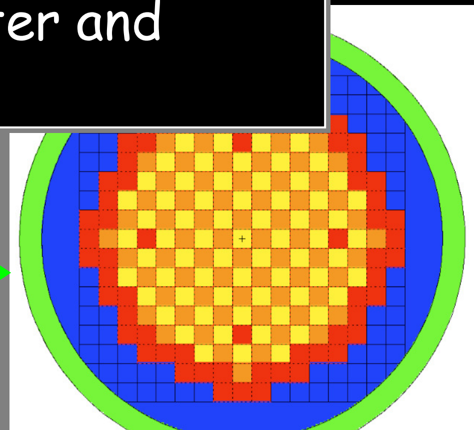
Core



zones
1 months



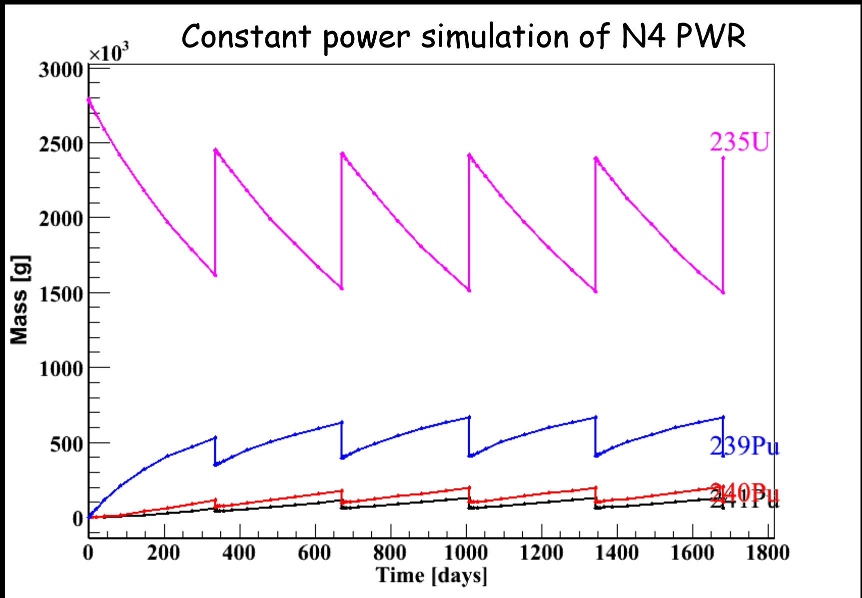
PWR : full core simulation.
Approx. : No control rod reactor driving yet : constant power, Boron diluted into water and mean k_{eff} =1

Cf. M. Fallot et al. ND2007 Conf. Proc.
Cf. B. Guillon et al. GLOBAL 2007 Conf. Proc.
Cf. L. Giot et al. PHYSOR 2008 Conf. proc.
Cf. F. Yermia et al. ICAPP 2009 Conf. Proc.

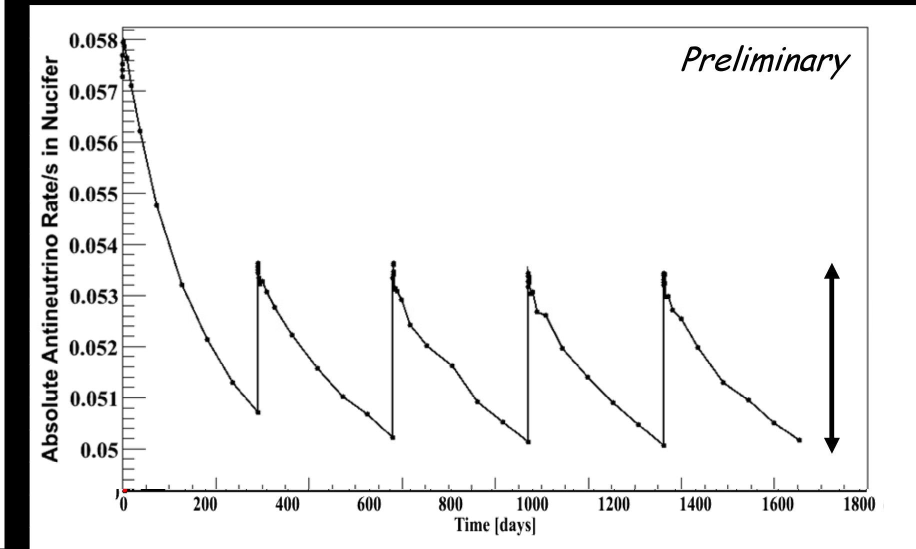
PWR simulation

Sensitivity to inputs of the simulation : Boron, T, evolution control,
Simulation of the refuelling of a reactor,
Proliferation scenario studies, folded by Nucifer response,
Simulation of CANDU reactors, research reactors…

Folded by Nucifer response @25m :



Antineutrino rate/s in Nucifer



6.4%

PWR refuelled every year :
250kg ^{239}Pu retrieval
900kg ^{235}U adjunction

Constant power : 4.27GW$_{th}$
Boron concentration 1000ppm
Mean k_{eff} = 1

Sensitivity : ~60 kg Pu in 4 days

M. Fallot et al., IAEA TAGS meeting, Jan. 27. 2009

Conclusions

- For important fission products in the antineutrino spectrum : Started a nucleus by nucleus study of the nuclear databases : comparison of the FP beta spectra (note in preparation)

- A lot of nuclei important for reactor antineutrinos are in the decay heat list and are Pandemonium nuclei

- Nuclei measured by Rudstam et al. have an important contribution to the antineutrino spectrum

- Compare with Greenwood's et al. data and see the effect on antineutrino spectrum

- Include new Valencia TAS measurements and see the effect on antineutrino spectrum

- Unkown nuclei : test QRPA/Gross Theory

What could we do ?

For both motivations : decay heat and reactor antineutrinos :

- Contribute in decay heat simulation : U and Pu isotopes, PWR ? Other (Th, future reactors…) ? (start : 2009, PhD V.M. Bui) => see the effect of new measurements for instance, or selection of priority list of nuclei

- Experiments : participate to planned experiments, to analysis ? (short term), propose new experiments for nuclei common to antineutrino and decay heat short lists (start : 2009, PhD V.M. Bui)

- Detector development (longer term …)

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