



Reactor Antineutrinos & Non Proliferation :

✗ Experimental needs for a better knowledge of the antineutrino spectra from ^{235}U , $^{239,241}\text{Pu}$, ^{238}U

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AAP Workshop - 26 sept. 06



Outline

- ❖ Development of MURE simulation tool for scenario studies...
- ❖ Previous measurements of antineutrino energy spectra
- ❖ « Dissection » of antineutrino energy spectrum of ^{235}U : FP contributions
- ❖ Interfacing MURE with nuclear databases and using an interface on the Beta-S code
- ❖ Conclusions and outlooks

Simulation effort

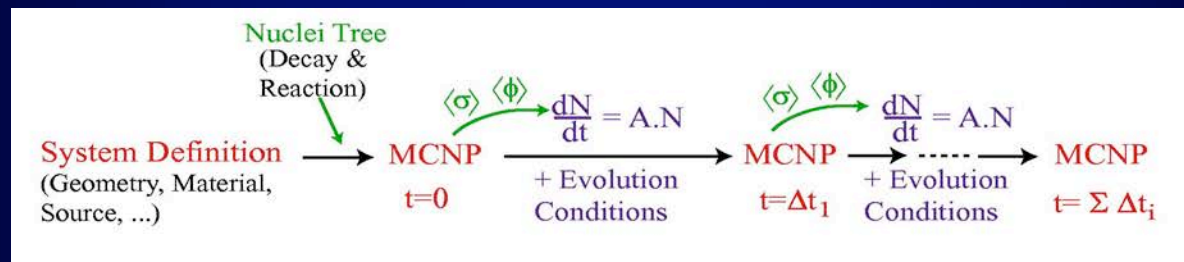
Fission product proportions vary with the fuel burn-up and with time because of the wide range of half-lives involved.

➔ Aim = Simulation of the anti-neutrino spectrum built from the fission product spectra



➔ For proper translation from beta to antineutrinos: individual end-points and shapes

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



MURE

MCNP Utility for Reactor Evolution

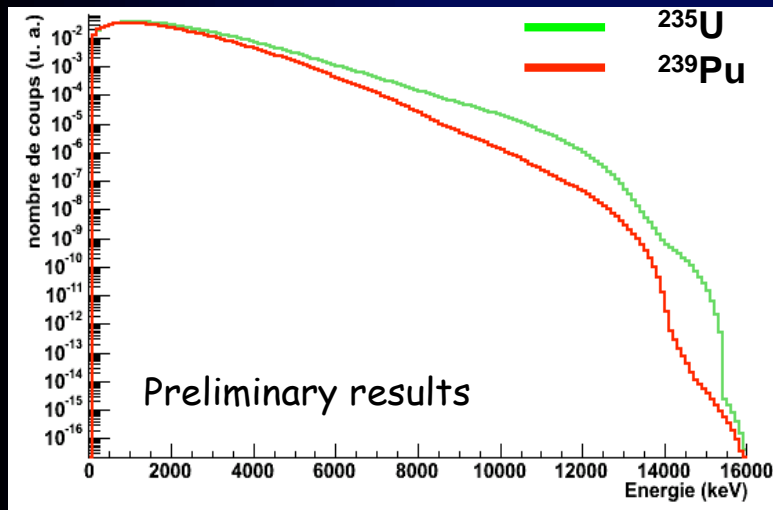
MURE : O. Méplan et al. ENC Proceedings (2005)





Simulation effort

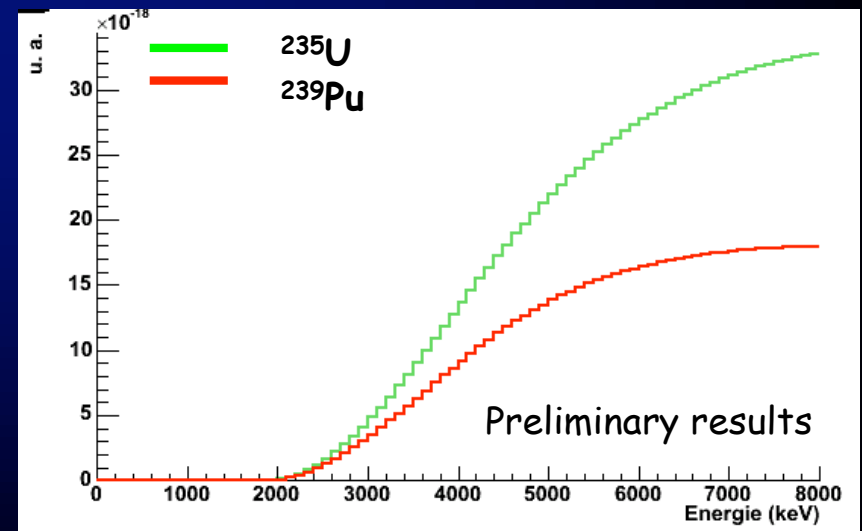
Developments to obtain a precise calculation of the evolution with time of the antineutrino spectrum in order to have a generic tool for proliferation scenario studies (even for rapid changes)



1 - Simulated spectra of emitted antineutrinos from the fission of ^{239}Pu and ^{235}U using MURE :



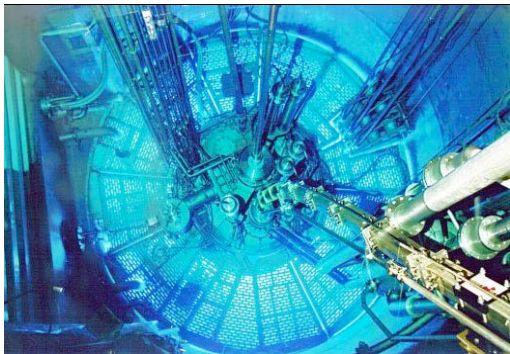
Relevant observables ?



2 - Folding with the detection cross-section

 Threshold : 1.804 MeV

3 - Cumulative spectrum in energy of antineutrinos 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 conversion : global fit including 30 arbitrary contributions: global shape uncertainty from 1.3% @ 3 MeV to 9% @ 8 MeV
- ✗ **FP contributions** : measurements of Tengblad et al. 111 nuclei @ISOLDE and OSIRIS don't agree with the experimental integral spectra (important errors : 5% at 4 MeV, 11% at 5 MeV and 20% at 8 MeV)
- ✗ **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 , $^{100-102}\text{Sr}$, $^{108-112}\text{Mo}$, $^{106-113}\text{Tc}$, $^{113-115}\text{Ru}$, $^{130-131}\text{Cd}$...



Examining the FP contributions

- Tengblad et al. included 370 nuclides in his spectrum including 111 exp. spectra from short half-lives, but also 177 BR and end-points (spin/parity ?), 25 known β -strengths and 67 extrapolated β -strength !!!
- First step = build back the spectrum obtained that time

- ✓ Need to read nuclear databases :

ENSDF : BR and endpoints, spin/parities when known !

JEFF3.1 : BR and endpoints, spin/parities when known

ENDF-B-VI : BR, endpoints, spin/parities + continuous spectra by Gross theory

JEF2.2 : contains some of the spectra measured by Tengblad et al.

- ✓ Beta Decay Theory to have the spectrum shape :

Fermi Theory of Beta Decay:

-Assumes a Weak interaction at a point.

$$\lambda = 2\pi |V_{fi}|^2 \rho(E_f) \text{ where } V_{fi} = \int \psi_f^* V \psi_i dv$$

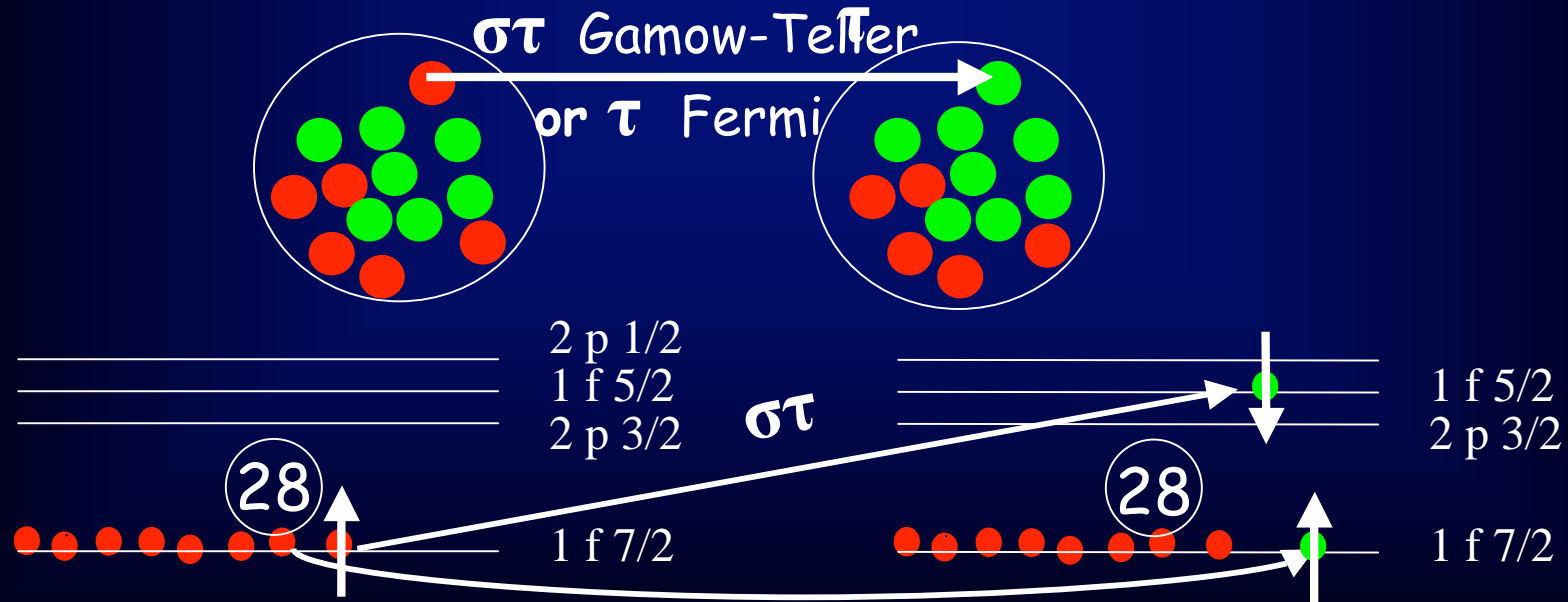
and $\rho(E_f) = dn/dE_f$ - no.of states in interval dE_f

Beta Decay Theory

The shape of the spectrum goes like:

$$N(Z, W)dW = g^2/2\pi^3 \times F(Z, W) \times pW(W_0 - W)^2 \times S_n(W) dW$$

Weak interaction coupling constant \rightarrow $g^2/2\pi^3$
 Fermi Function \rightarrow $F(Z, W)$
 Momentum in $m_e c^2$ units \rightarrow p
 Total electron energy in $m_e c^2$ units \rightarrow W
 Nuclear Matrix element \rightarrow $S_n(W)$
 End point \rightarrow W_0
 Shape factor for allowed and nth forbidden transition \rightarrow $S_n(W)$



β -decay and Classification of β -spectra :

Classification	ΔJ	$\Delta\pi$	logft
Allowed	$0, \pm 1$ ($0+ \not\rightarrow 0+$)	No	4-6
1st forbidden non-unique	$0, \pm 1$	Yes	6-10
1st forbidden unique	± 2	Yes	7-10
2nd forbidden non-unique	± 2	No	11-14
2nd forbidden unique	± 3	No	14
3rd forbidden non-unique	± 3	Yes	17-19
3rd forbidden unique	± 4	Yes	18

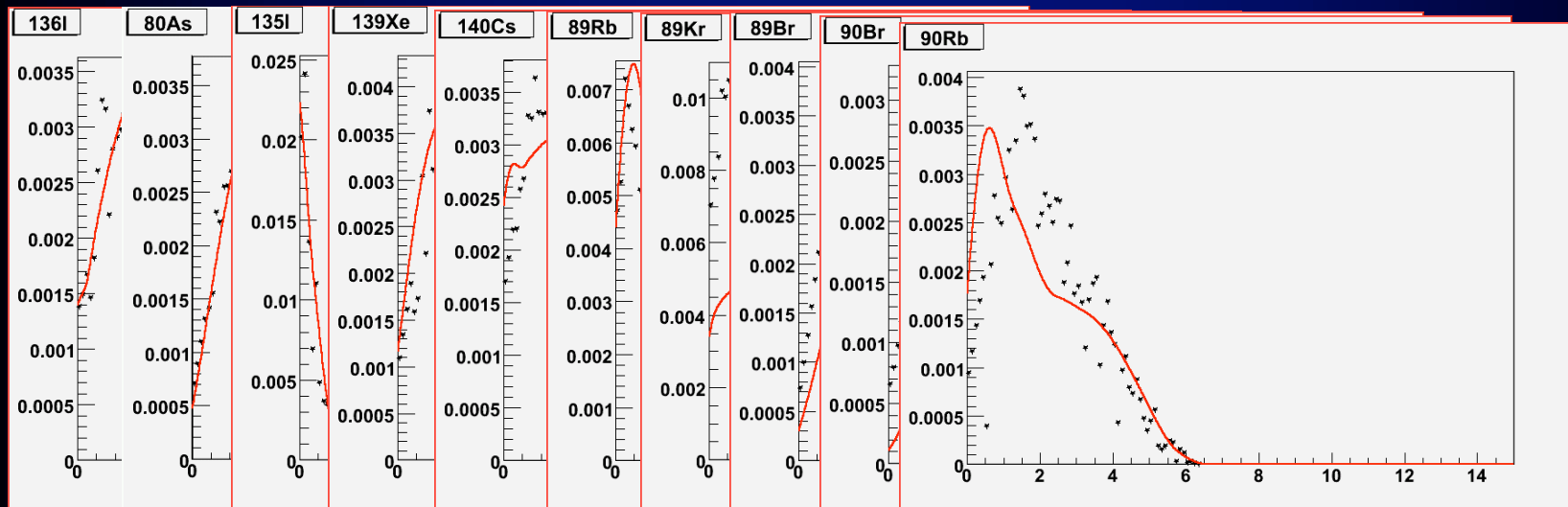
✘ Transition rate $\lambda = \frac{0.693}{t_{1/2}}$. We introduce $ft_{1/2} \propto \text{Const.} / |M_{fi}|^2$

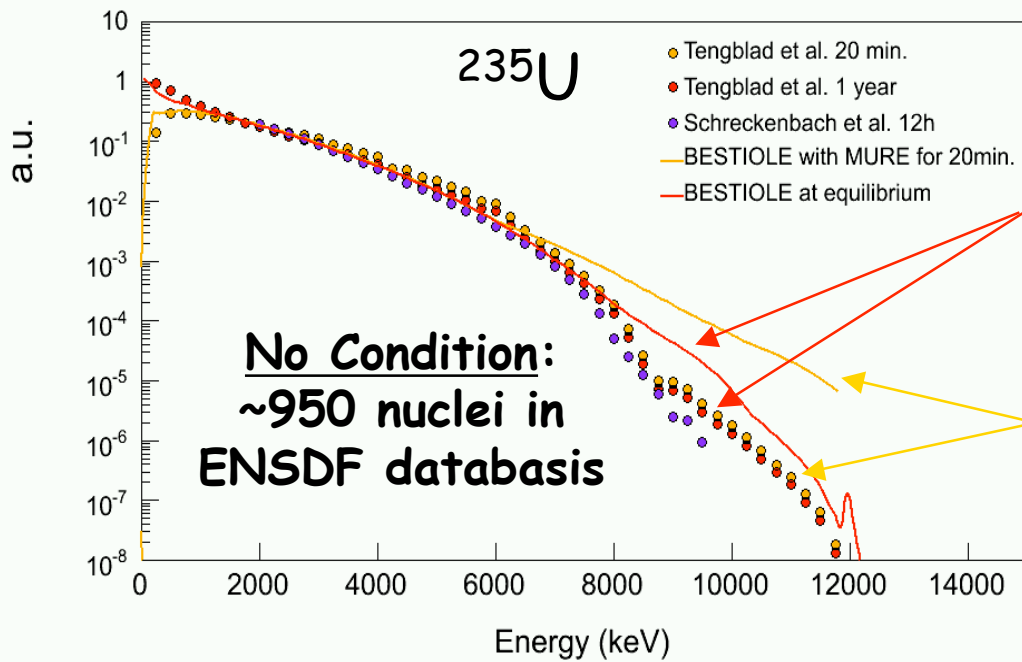
✘ The vast majority of β -transition are classified as allowed type

✘ « Shape factors » : emphasize the high energy region of the spectra compared with allowed spectra

« BESTIOLE » package : interface by D. Lhuillier (CEA/SPhN) on BETA-S code from Oak Ridge*

- ✓ Reads ENSDF Branching ratios, End-points and spin/parities
 - ✓ Allowed, 1st, 2nd and 3rd forbidden unique transitions are **explicitly represented**
 - ✓ 1st forbidden non-unique : shape factor $S1(W)$ independent of energy = **idem as allowed transitions**
 - ✓ 2nd and 3rd forbidden non-unique : original approximation = assumed to have an allowed shape
- ➡ **Modified to take the 1st and 2nd forbidden unique shape instead**



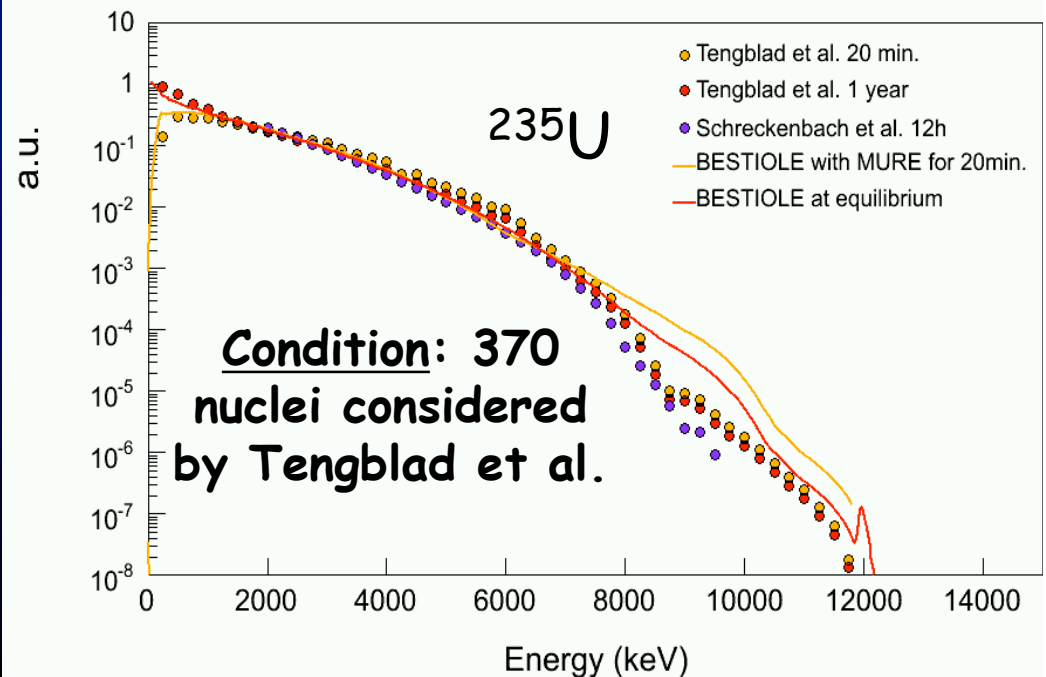


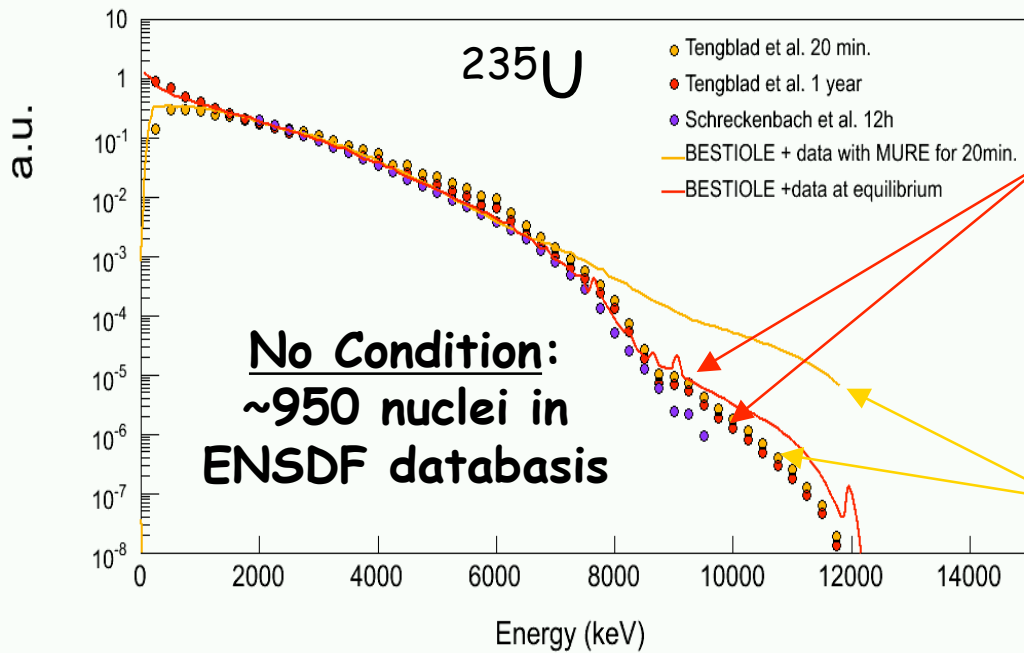
Results

Tengblad et al. 1 year of irradiation
Compared with BESTIOLE for ~950
nuclei with cumulative yields

Tengblad et al. 20min. of irradiation
Compared with MURE 20min. evolution
using the spectra from BESTIOLE

Including more nuclei:
among them exotic nuclei, with
short half-lives, high end-
points, and more numerous
forbidden transitions



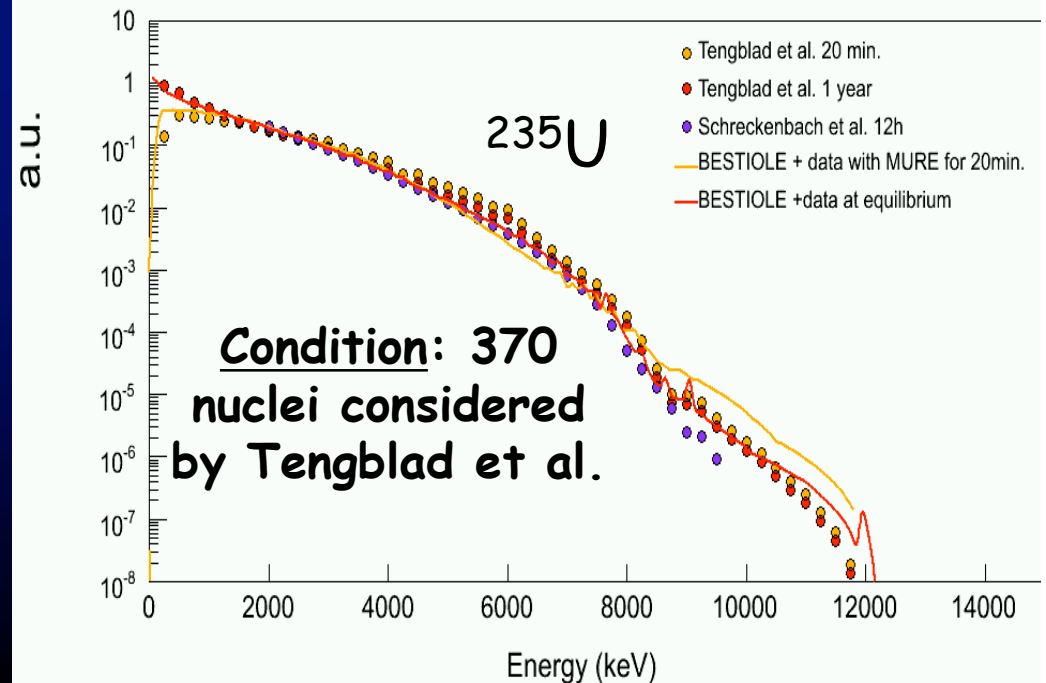


Results

Tengblad et al. 1 year of irradiation
Compared with BESTIOLE and 75
exp. spectra among the 111 measured
by Tengblad et al. for ~950 nuclei
with cumulative yields

Tengblad et al. 20min. of irradiation
Compared with MURE 20min. evolution
for BESTIOLE and 75 exp. spectra

- Including exp. spectra :
- Nearly reconstitutes Tengblad spectrum
 - We clearly see some more nuclei should be taken into account at high energy + more exp. spectra when forbidden non-unique transition !!!
- Solving the shape discrepancy with Schreckenbach et al. ?



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

- ✘ Double-Chooz phase 1: when only far detector,
=> better precision on the reactor $\bar{\nu}_e$ spectrum very useful
- ✘ Double-Chooz phase 2: best measurement of reactor $\bar{\nu}_e$ spectrum
and flux $\sim >10^5$ evts/y

- ✘ Nuclear reactor physics and safety (decay heat calc.)
/future (Gen. IV) reactors (decay heat + β -delayed n)

- ✘ Nuclear structure (exotic nuclei), nuclear astrophysics for the most exotic ones...

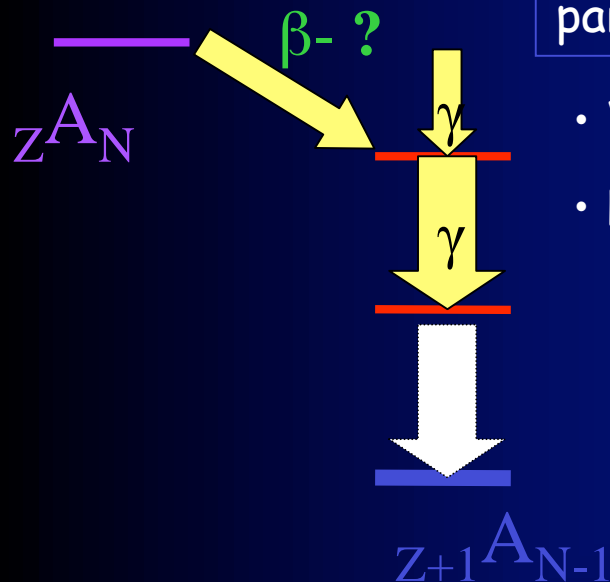
- ✘ Astroparticle physics : future neutrino experiments (relic Supernovae...) $\bar{\nu}$ spectrum never measured beyond 8 MeV



Strong common points with measurements for reactor decay heat calculation in nuclear reactors

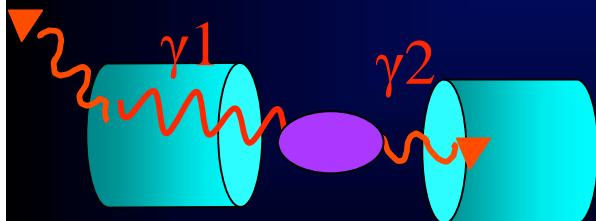
- Data required-cross-sections, fission yields, decay half-lives, mean beta and gamma energies, neutron capture cross-sections and uncertainties in these data.

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



- We use our *Ge* detectors to construct the decay scheme
- From the γ -balance we extract the β -feeding

Low efficiency of *Ge* detectors at high energy => Pandemonium effect = displacement of the β -strength (overestimation of high energies)

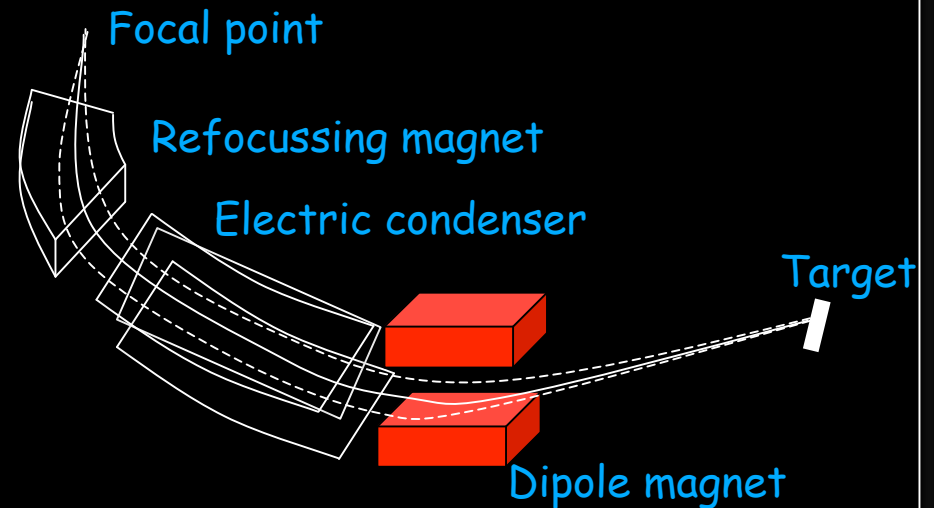


« Pandemonium effect » = indication to explain the discrepancy between Tengblad and Schreckenbach ?

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

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

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



⇒ Test of the simulation of the evolution of beta spectra from isobaric chains $A=90,94$

⇒ Analysis on going..., PhD thesis of S. Cormon

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

Good point: discussions started with collaboration for decay heat related measurements (J.L.Tain, W. gelletly et al.) on ALTO: some nuclei in common

✘ 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

Conclusions and outlooks

- ❖ Possible origins of discrepancies between previous measurements :
 - lack of short half-life nuclei
 - highly forbidden transitions more important at high energy
 - Pandemonium effect in nuclear data basis ?
- ❖ Comparison between ENSDF and ENDF, JEFF...
- ❖ Theoretical point of view : Gross Theory for β - decay, Microscopic models ?
- ❖ Isolate the most pertinent nuclei to be measured (forbidden non-unique transitions) that influence the spectrum shape (especially high energy part)
- ❖ Proposal to use the ALTO facility, GANIL... ^{238}U beta spectrum ?
+ Moscow-Kurchatov initiative...