THE SUMMATION METHOD FOR REACTOR ANTINEUTRINO FUNDAMENTAL AND APPLIED PHYSICS

M. Fallot[1]

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INT Seattle
Reactor Antineutrino Workshop

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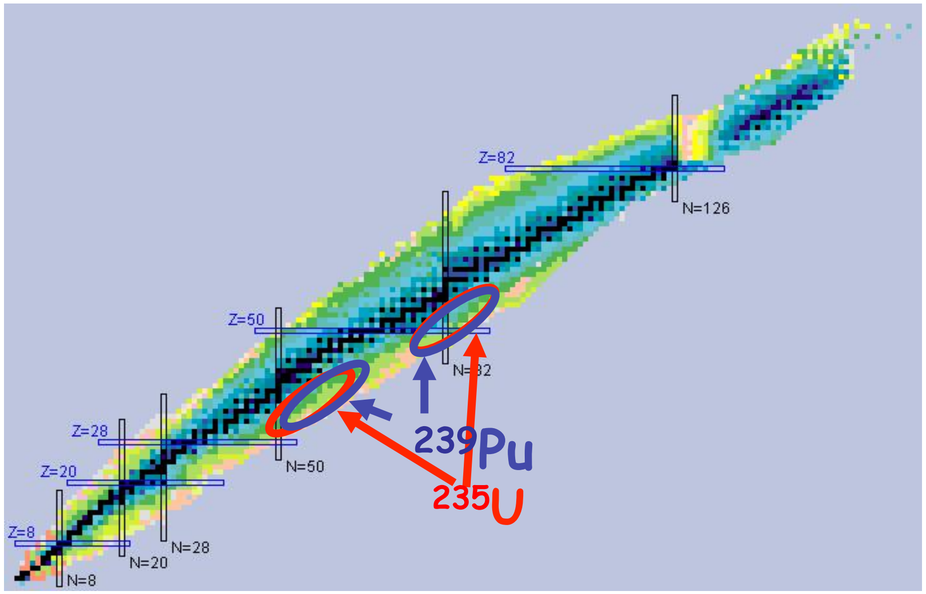
IAEA

Outline

- Introduction
- Summation Method for Antineutrino Energy Spectrum
- On the Nuclear Data Side: Synergy with Decay Heat, Pandemonium Effect, Total Absorption Spectroscopy Technique
- New Reactor Antineutrino Spectra With the Summation Method
- Examples of Antineutrino Spectra for Innovative Fuels and Reactors
- Conclusions and Outlooks

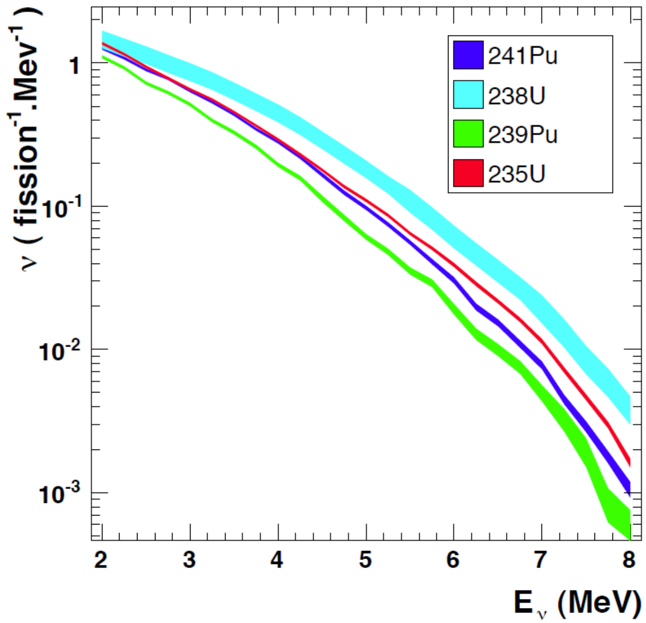
Reactor Antineutrinos

	^{235}U	^{239}Pu
E_f (MeV)	**201.9**	**210.0**
$\langle E_\nu \rangle$ (MeV)	**1.46**	**1.32**
$\langle N_\nu \rangle$ (E>1.8MeV)	**5.58 (1.92)**	**5.09 (1.45)**



Most of Fission Products (FP) are neutron-rich nuclei, undergoing β - decay

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-} + \boxed{\bar{\nu}_e}$$



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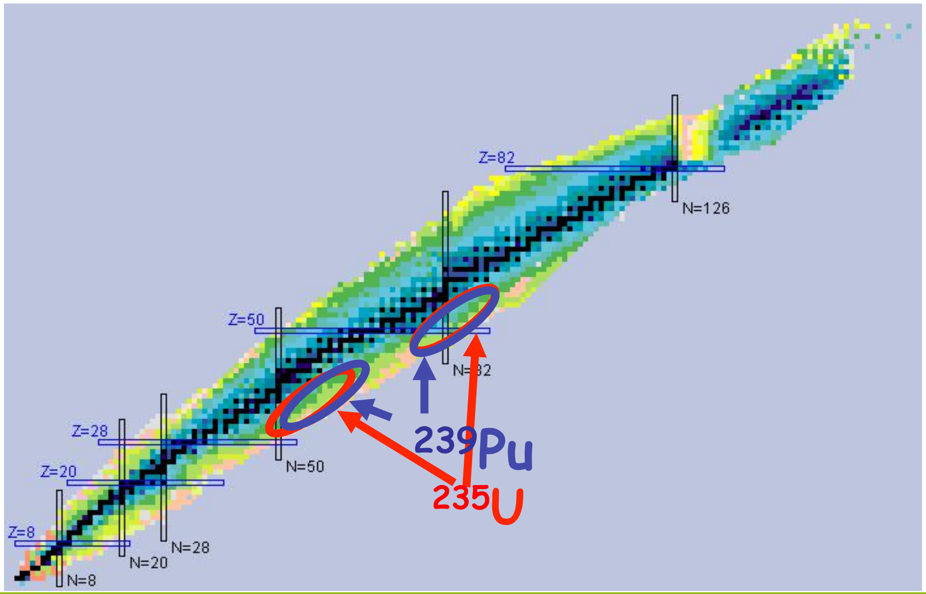

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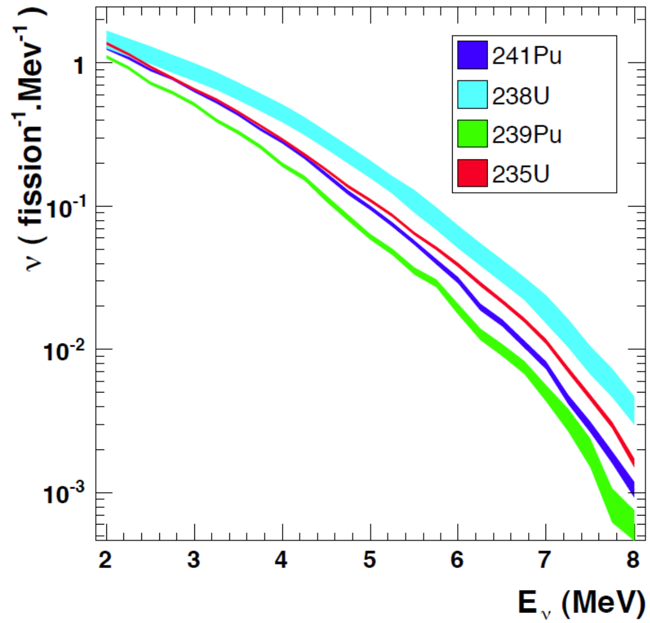


⇒ **Power Reactors are copious antineutrino emitters => neutrino physics = oscillation parameter search: θ_{13}, search for sterile neutrinos (« reactor anomaly »)**

⇒ **Use the discrepancy between antineutrino flux and energies from U and Pu isotopes to infer reactor fuel isotopic composition => reactor monitoring, non-proliferation and interest of the IAEA** (see IAEA Report SG-EQGNRL-RP-0002 (2012).)

Reactor antineutrinos

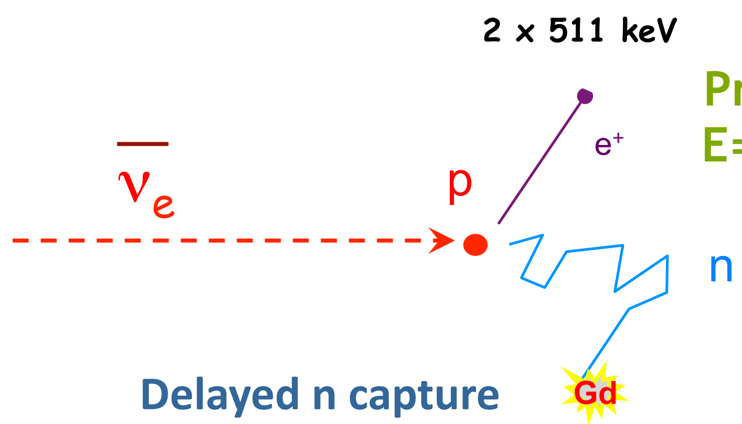
- **Standard nuclear power plant 900 MWe :**

$$\frac{2800\ \mathrm{MW_{th}}}{200\ \mathrm{MeV}} \times 6\ \bar{\nu}_e \qquad \sim\ 5 \cdot 10^{20}\ \bar{\nu}_e / s$$

- **Usually detection through inverse-β process on quasi-free protons :**

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

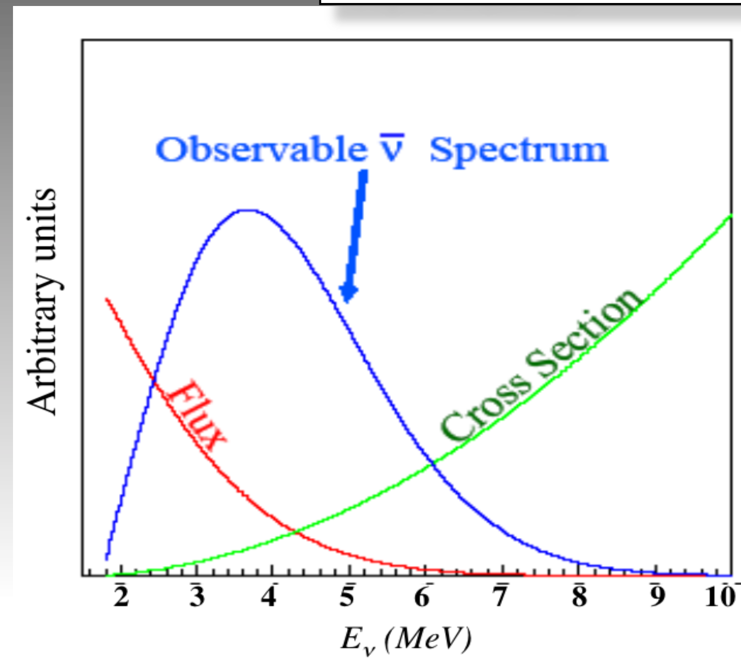
- ❑ Reaction threshold : **1.8 MeV**
- ❑ Cross section $(\alpha\, E_n^2)$: **$\langle\sigma\rangle \sim 10^{-43}\mathrm{cm}^2$**



Prompt e^+
E=1-8 MeV

Delayed n capture
Gd nuclei
Σγ ~ 8 MeV

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



- ➢ **Time correlation : τ ~ 30μs**
- ➢ **Space correlation : < 1m**

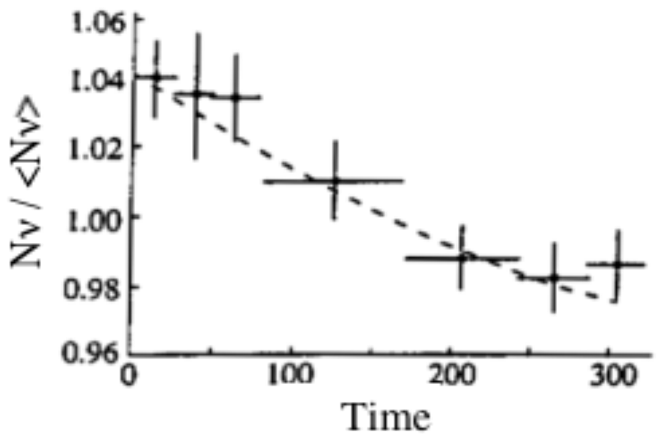
Reactor Antineutrino & Safeguards

✓ **Direct relationship between antineutrino flux and energy with thermal power and fuel content (burnup) was proved experimentally by the neutrino experiments (Rovno, Bugey, Chooz…) and more recently by the dedicated SONGS experiment (LLNL)**

Rovno experiment:

- Detector: 1m^3 Gd-doped LS @ 18 m
- Reactor ~ 1.3 GWth
- Detection efficiency close to 50%
- Daily power monitoring and burnup :

V.A. Korovkin et al., Atomic Energy, 65, No. 3, 712-718 (1988)
Yu. V. Klimov et al., Atomic Energy, v.76-2, 123, (1994)



✓ **Several research axes worldwide:**

- **Applications of the antineutrinos: reactor simulations (future reactor designs, innovative fuels…)**
- **R&D of antineutrino detectors devoted to nuclear safeguards: US (SONGS, …), Japan (Tohoku, Tokyo), Russia (DANSS), Brazil (ANGRA), Italy (CORMORAD), France (Nucifer), GB (MARS/SOLiD), …**
- **Improvement of our knowledge on the reactor antineutrino energy spectra: Link with Nuclear Data**
- **Synergy with neutron detection techniques**

Antineutrino Detection for Reactor Monitoring

- First meeting @ IAEA in 2003, with Agency members and neutrino physics experts
- 2008 : Expert meeting @IAEA (physicists & inspectors) : IAEA Report « Final Report of the Focused Workshop on Antineutrino Detection for Safeguards Applications », STR-361, Feb. 2009.
- 2010 : Symposium on International Safeguards: Preparing for Future Verification Challenges: Creation of an ad-hoc WG
  1st IAEA Ad-Hoc WG meeting in Sept. 2011, IAEA Report " Final Report of the Focused Workshop on Antineutrino Detection for Safeguards Applications », STR-361, Department of Safeguards, 2012.
- Creation of a sub-WG devoted to antineutrino detection of the Novel technologies WG of the European Safeguards Research and Development Association (ESARDA) (http://esarda2.jrc.it/internal_activities/WG-NT-NA/index.html)
- ESARDA NA/NT WG meeting: @35rd ESARDA meeting: May 2013, Belgium, Key words: antineutrino detection, R&D, compact detectors, PSD, actual and future reactors, simulations, proliferation scenarios, NUCLEAR DATA …

Last ESARDA Meeting:
https://esarda.jrc.ec.europa.eu/index.php?option=com_content&view=article&id=70&Itemid=238 and proceedings associated to the antineutrino detection in the NA/NT session;

Fundamental Neutrino Physics

First Double Chooz, Daya-Bay and Reno theta13 results published in Phys. Rev. Lett. in 2012 !

Y. Abe et al Phys. Rev. Lett. 108, 131801, (2012)
F. P. An et al., Phys. Rev. Lett. 108, 171803 (2012).
J. K. Ahn et al., Phys. Rev. Lett. 108, 191802 (2012)

⇒ **The Double Chooz experiment has devoted efforts to new computations of reactor antineutrino spectra**

⇒ **Two methods were re-visited:**

- One relying on the conversion of integral beta spectra of reference measured by Schreckenbach et al. in the 1980's at the ILL reactor (thermal fission of ^{235}U, ^{239}Pu and ^{241}Pu integral beta spectra): use of nuclear data for realistic beta branches, Z distribution of the branches…

- The other being the summation method, summing all the contributions of the fission products in a reactor core: only nuclear data : Fission Yields + Beta Decay properties

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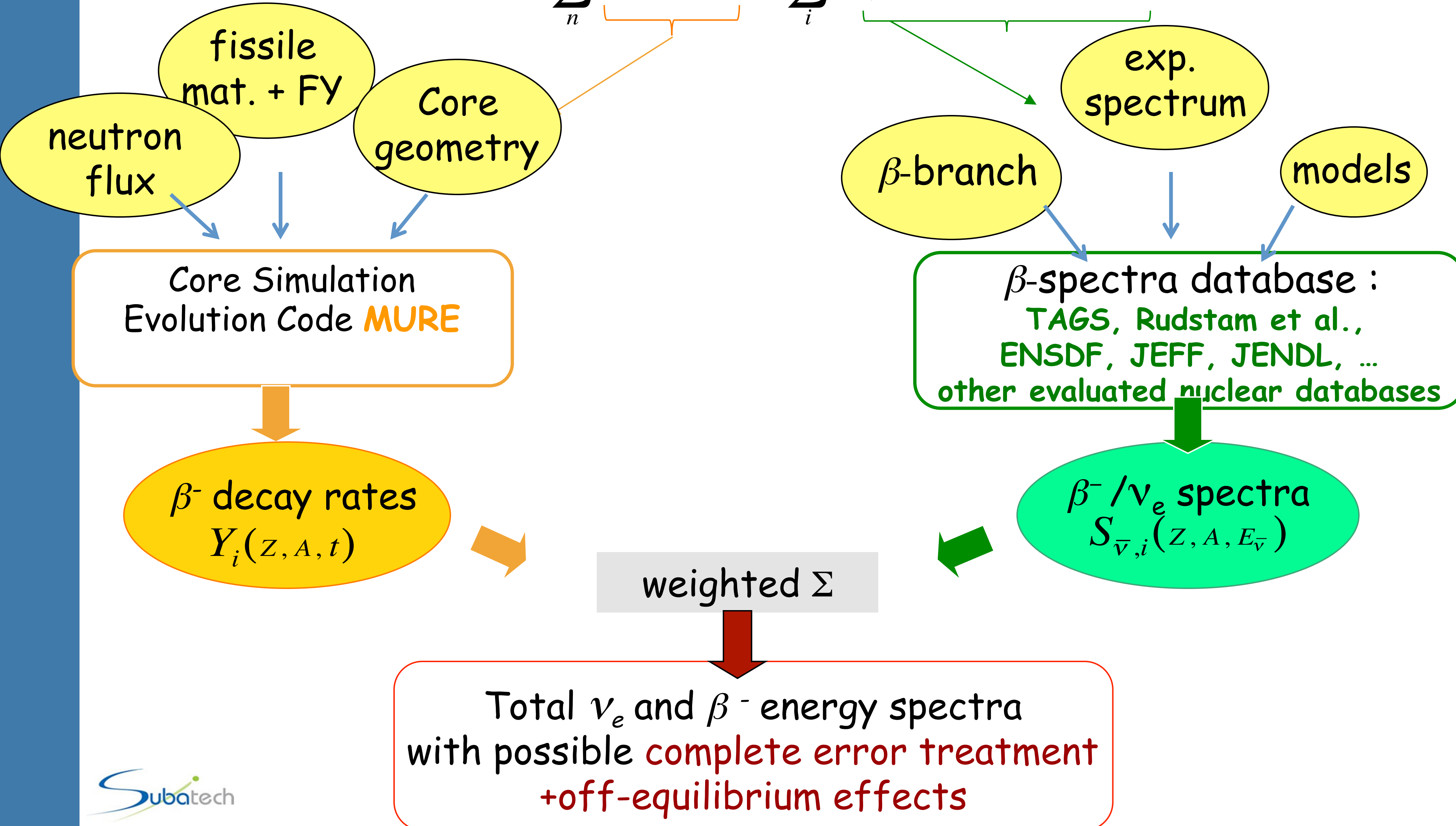
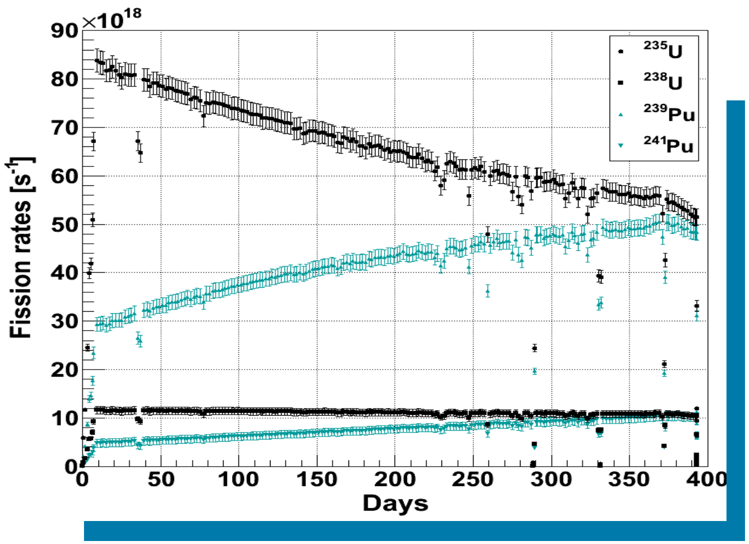
Summation Method: Method based on individual fission product beta decay summation

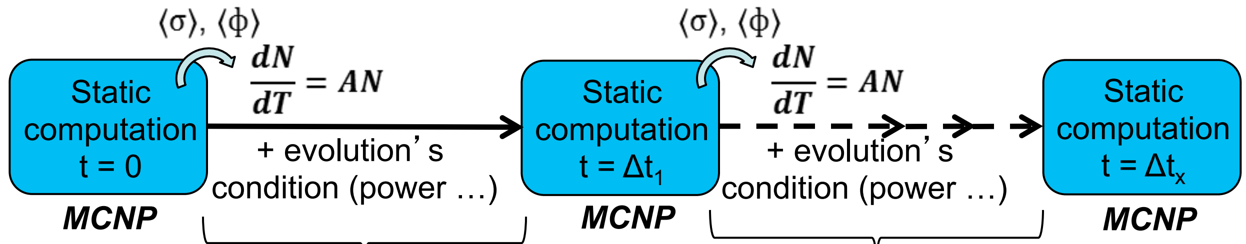
$$N(E_\nu) = \sum_n \underbrace{Y_n(Z,A,t)} \cdot \sum_i \underbrace{b_{n,i}(E_0^i) P_\nu(E_\nu, E_0^i, Z)}$$



The MURE* Code

- The MURE Code (MCNP Utility for Reactor Evolution) :
  - C++ interface to the Monte Carlo code MCNP (static particle transport code)
  - Open source code available @ NEA: http://www.oecd-nea.org/tools/abstract/detail/nea-1845
  - Used for the 1st phase of the Double Chooz experiment





Material evolution: Resolution of Bateman differential equations

$$\frac{\partial N_i}{\partial t} = \underbrace{-\lambda_i N_i + \sum_j \lambda_j^{j\to i} N_j}_{\textit{decays}} + \underbrace{\sum_{j'} N_{j'} \langle\sigma_{j'}\rangle^{j'\to i}\langle\phi\rangle - N_i \sum_{\forall r} \langle\sigma_i\rangle^{(r)}\langle\phi\rangle}_{\textit{reactions induced by neutron}}$$

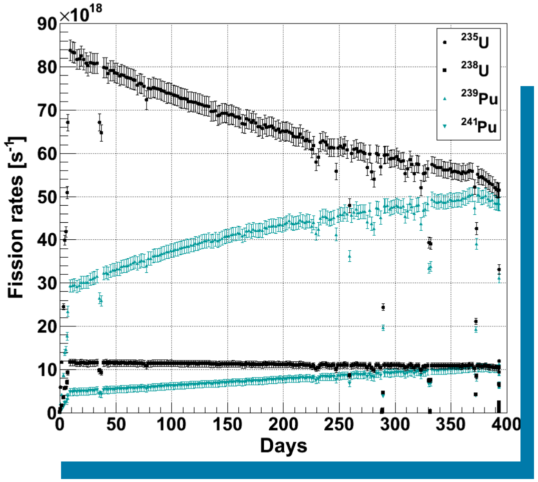
➡ Outputs provided: keff, neutron flux, inventory, reaction rates + adapted to compute antineutrino spectra

➡ Development of a complete core simulation with a follow up of core operating parameters

➡ Can be used also for simple geometries: ILL spectra computation

A. Onillon's PhD (Univ. Of Nantes) in prep. + Takahama benchmark: C. Jones et al. PRD 86 (2012) 012001

DChooz: Antineutrino flux and spectrum prediction



- Far detector data only
- No-Oscillation ⇒ reactor flux prediction via core simulations
- Normalisation to the Bugey-4 cross-section with far detector only

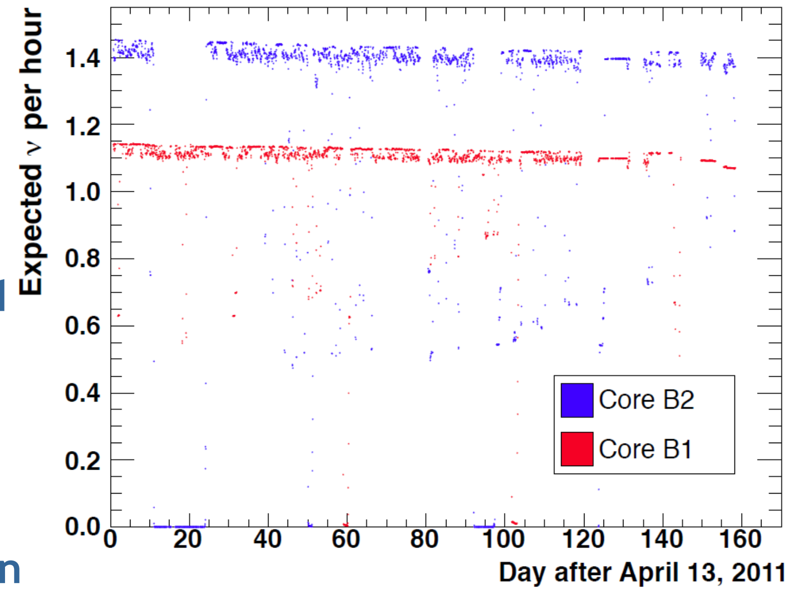
⇒ Reduced reactor systematics:

Full core simulations with the MURE code, with a follow-up of thermal power and boron concentration (>700h CPU for a complete cycle)

Numerical computation of the systematic error associated to the fission rates with MURE over the fuel cycle

⇒ Fractions of fissions per isotope ^{235}U=49.6%, ^{239}Pu=35.1%, ^{241}Pu=6.6%, and ^{238}U=8.7% and the fission rate covariance matrix.

⇒ Resulting relative uncertainties on the above fission fractions are ±3.3%, ±4%, ±11.0% and ±6.5%



Total reactor error: 1.7%

Accurate reactor simulations keep the contribution of fission fraction uncertainties low

Ingredients to Build Beta and Antineutrino Spectra

- $N_\beta(W) = K\, pW(W-W_0)^2 F(Z,W) L_0(Z,W) C(Z,W) S(Z,W) G_\beta(Z,W)(1+\delta_{WM} W)$

Where $W=E/m_e c^2$, K = normalization constant,

$pW(W-W_0)^2$ = phase space, to be modified if forbidden transitions

$F(Z,W)$ = „traditional" Fermi function

$L_0(Z,W)$ and $C(Z,W)$ = finite dimension terms (electromagnetic and weak interactions)

$S(Z,W)$ = screening effect (of the Coulomb field of the daughter nucleus by the atomic electrons)

$G_\beta(Z,W)$ = radiative corrections involving real and virtual photons

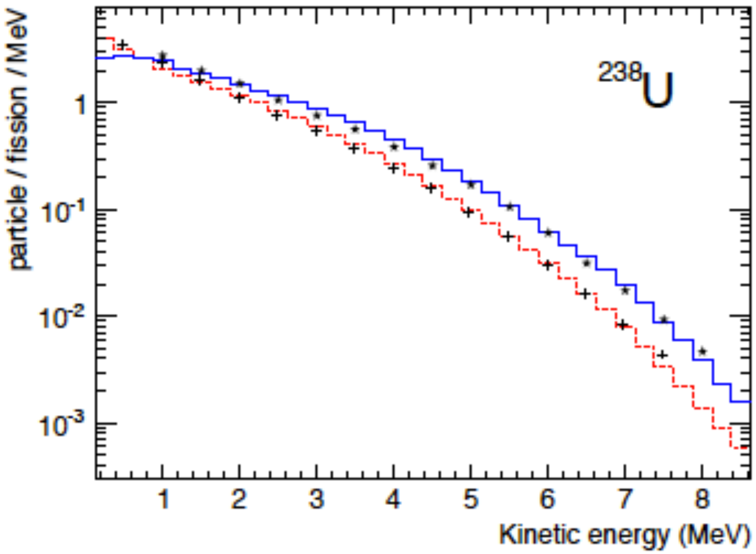
δ_{WM} = weak magnetism term

The first results were published in Th.A. Mueller et al, Phys.Rev. C83(2011) 054615:

And only radiative corrections, coulomb and WM corrections were taken into account, following Vogel's prescription

- **Summation method:** Energy conservation for conversion into antineutrino spectrum, for each beta branch of each fission product + realistic Z distribution of the fission products

« Summation » Method with the MURE* code



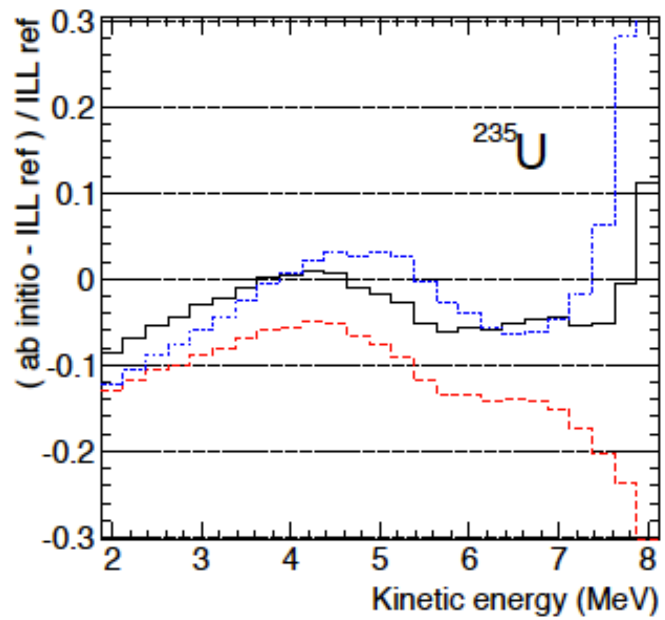
***MCNP Utility for Reactor Evolution:**

- Computes the fission product distributions to couple with beta decay nuclear databases
- Computes off-equilibrium effects
- Prediction of <u>any antineutrino energy spectrum</u> for individual fissible nuclei or full reactor cores, for neutrino physics or non proliferation

But Pandemonium effect:

Overestimate of the reference spectra @ high energy + shape distortion

⇒ Requires new measurements of fission product beta decay properties



***MCNP Utility for Reactor Evolution:** http://www.nea.fr/tools/abstract/detail/nea-1845.

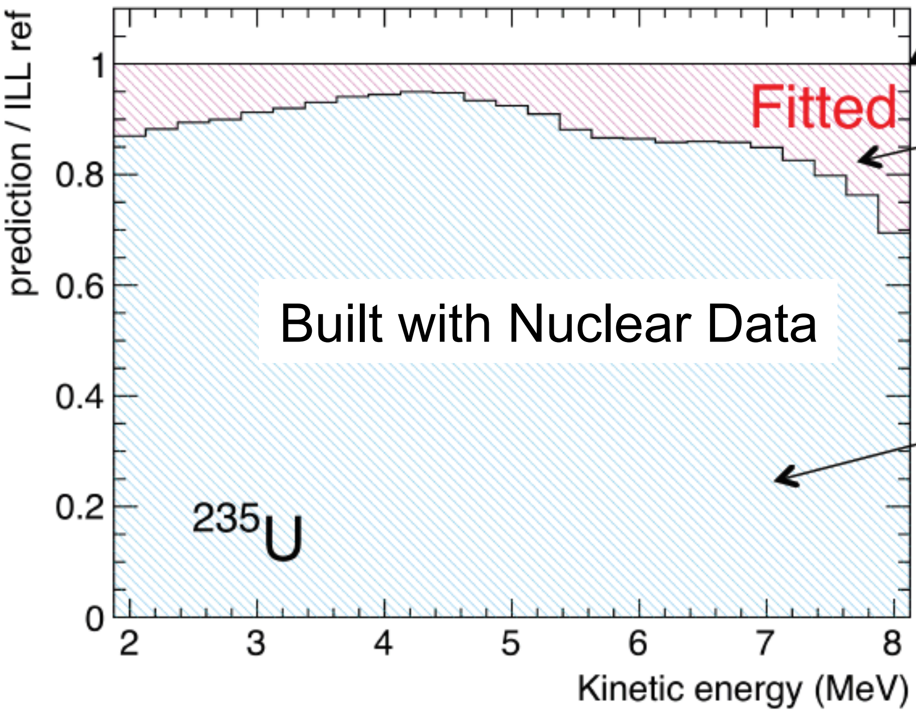
Th. Mueller et al. Phys. Rev. C 83, 054615 (2011).,

Newly Converted Spectra

Th.A. Mueller et al, Phys.Rev. C83(2011) 054615

- **Assume a 10% error on the summation method spectra for all the bins,** based on the discrepancy with ILL spectra **=> no complete error estimate yet**
- Assuming that summation method not yet precise enough, **develop a mixed approach using nuclear databases + fictive branches to reproduce the ILL spectra**

Ratio of Prediction / Reference ILL data

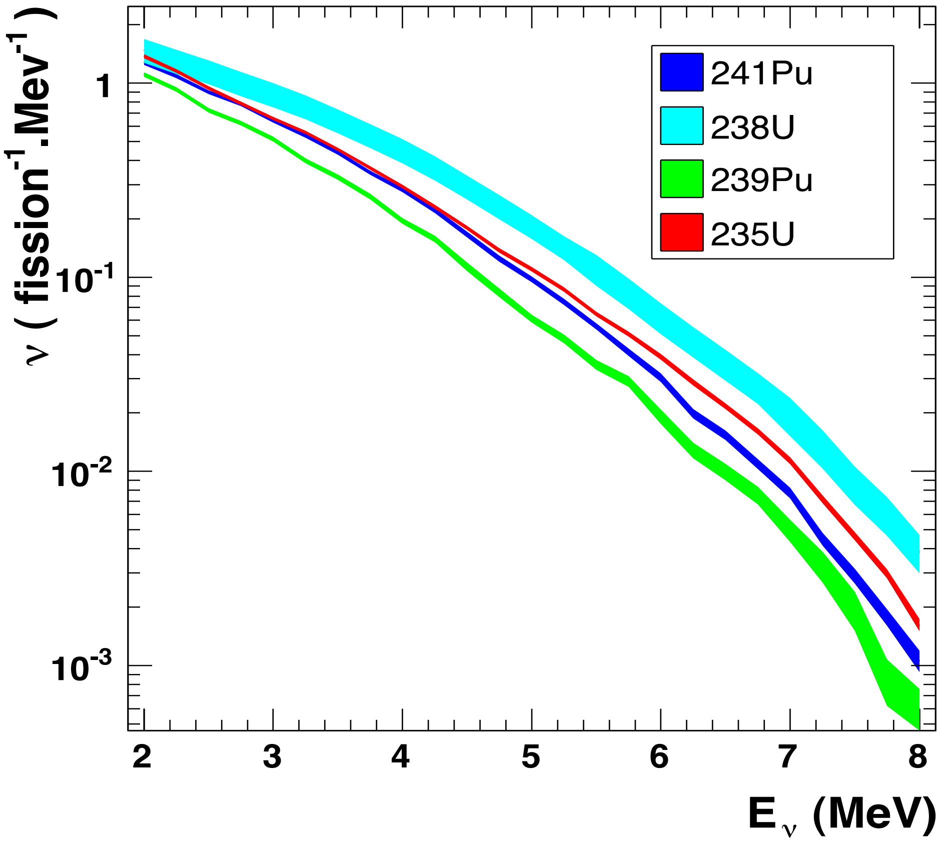


ILL electron data anchor point

- Fit of residual: five effective branches are fitted to the remaining 10%
  $\Rightarrow$ Suppresses error of full Summation Approach, if assumption that ILL data = only reference

- "true" distribution of all known β-branches describes >90% of ILL e data
  $\Rightarrow$ reduces sensitivity to virtual branches approximations

Newly Converted Spectra



- Recent re-evaluations by
- Th.A. Mueller et al, Phys.Rev. C83(2011) 054615.
- P. Huber, Phys.Rev. C84 (2011) 024617

- Off-equilibrium corrections included (computed with MURE)

- Summation calculations, database comparisons and fission product distribution= new ^{238}U prediction

Recent works defining new reference on the neutrino flux prediction for neutrino physics

Newly Converted spectra…

- ILL data = unique and precise reference => converted ν spectra = **+3% normalization shift with respect to old ν spectra (>threshold)**, similar results for all isotopes (^{235}U, ^{239}Pu, ^{241}Pu)

⇒ **Origin of the bias identified:**

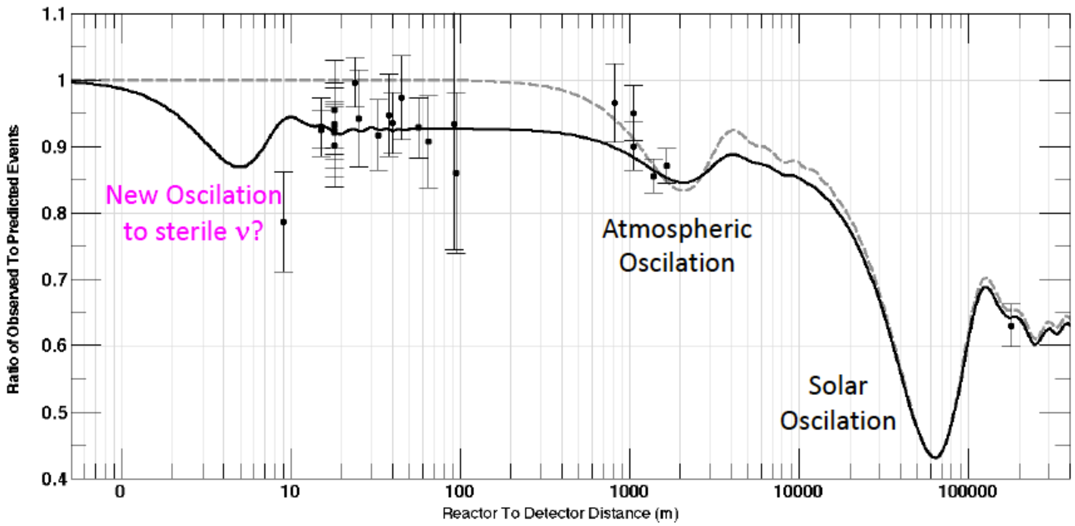
- ILL conversion procedure (only virtual branches): 2 independent biases:
  - ❑ Low energy: correction to Fermi theory should be applied at branch level
  - ❑ High energy: mean Z fit is not accurate enough.

⇒ « Reactor anomaly »: all reactor neutrino experiments are below the prediction (G. Mention et al. Phys. Rev. D83, 073006 (2011)).

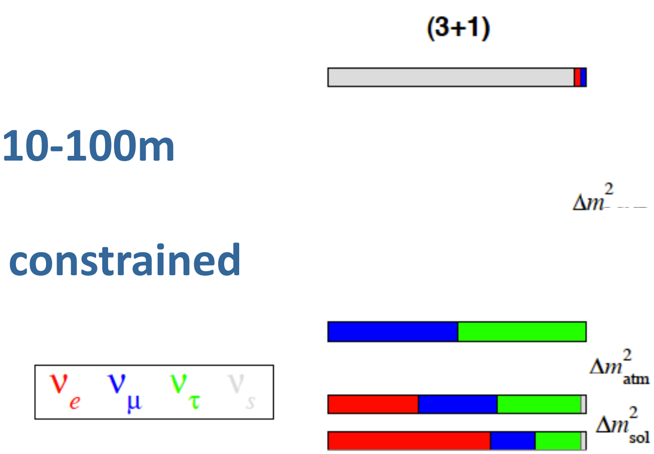
Sterile Neutrino hints ?

- **Reactor Anomaly:**
  - converted ν spectra = ˜+3% normalization shift with respect to old ν spectra, similar results for all isotopes (^{235}U, ^{239}Pu, ^{241}Pu)
  - Neutron life-time
  - Off-equilibrium effects

2 flavour simple scheme :
$P_{Osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2_{[eV2]} L_{[m]} / E_{[MeV]})$



G. Mention et al. Phys. Rev. D83, 073006 (2011)



=> Light sterile neutrino state ? could explain L=10-100m anomalies, $\Delta m^2 \approx 1$ eV^2

• candidate can't interact via weak interaction : constrained by LEP result on 3 families

=> so can only exist in sterile form

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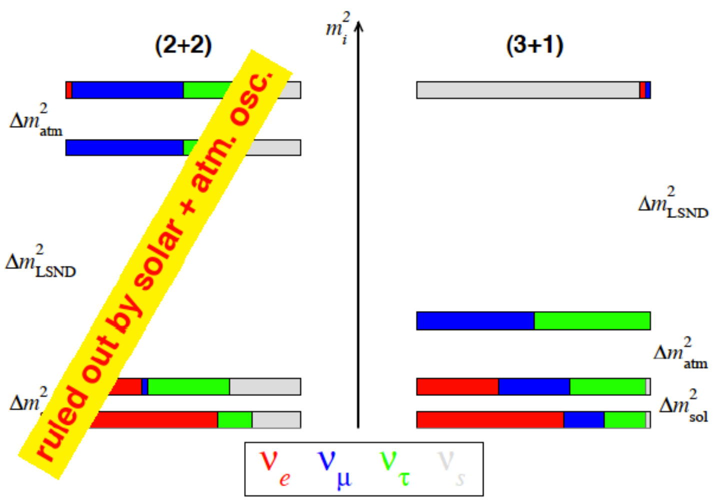
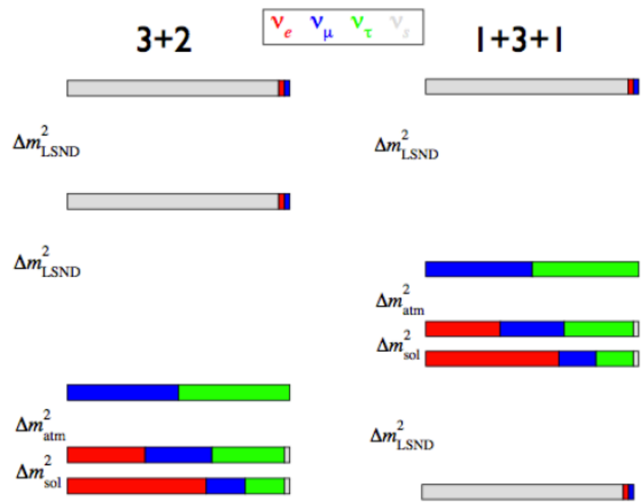
arXiv:1303.3011v2 [hep-ph]

« An explanation of all hints in terms of oscillations suffers from severe tension between appearance and disappearance data. The best compatibility is obtained in the 1+3+1 scheme with a p-value of 0.2% and exceedingly worse compatibilities in the 3+1 and 3+2 schemes. »

Global Analysis by J. Kopp, P. A.N. Machado, M. Maltoni, T. Schwetz [arXiv:1303.3011]



3+1: small perturbation to 3-active case



Peres, Smirnov, hep-ph/0011054; Sorel, Conrad, Shaevitz, hep-ph/0305255

See T. Schwetz's talk @ APC, 2013

Newly Converted spectra…

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⇒ « Reactor anomaly »: all reactor neutrino experiments are below the prediction (G. Mention et al. Phys. Rev. D83, 073006 (2011)).

⇒ Now looking for sterile neutrinos as a potential explanation to the reactor anomaly: Nucifer exp., + numerous projects: SOLiD (UK), STEREO (France), SCRAMM(US-Ca), Neutrino-4 (Russia), DANSS(Russia), + Mega-Curie sources in large ν detector… (white paper: K. N. Abazajian et al., http://arxiv.org/abs/1204.5379.)

⇒ Other explanations still possible: large uncertainty for Weak Magnetism term => could change normalization of spectra, or normalization of ILL data

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On the Nuclear Data side…

The reactor antineutrino estimate is not the only one to suffer from the Pandemonium Effect: Similar problem for Reactor Decay Heat (initiated by Yoshida et al. see Nuclear Science NEA/WPEC-25 (2007), Vol. 25**)**

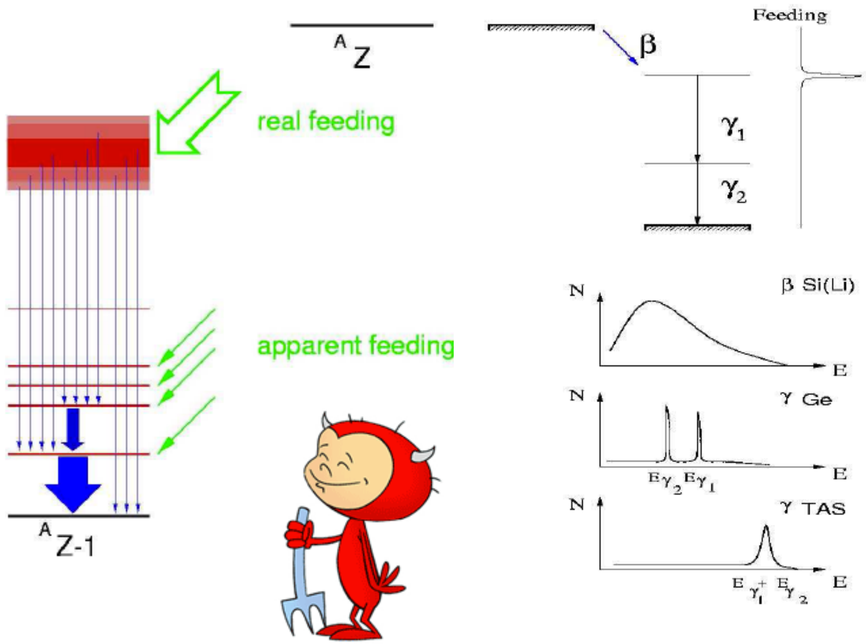
$\Rightarrow$ **TAS experiments**

TAS Technique

Pandemonium effect**:

Due to the use of Ge detectors to measure the decay schemes: lower efficiency at higher energy

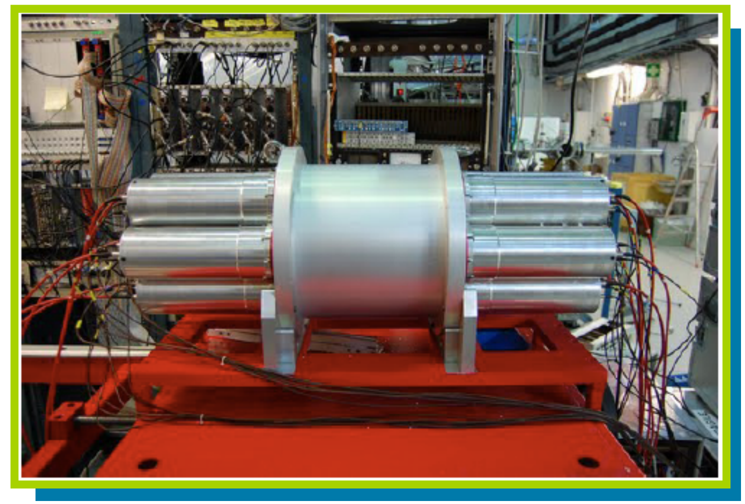
→ underestimate of β branches towards high energy excited states: overestimate of the high energy part of the FP β spectra



Picture from A. Algora

Solution: Total Absorption Spectroscopy (TAS)

Big cristal, 4π => A TAS is a calorimeter !



- 12 BaF_2 covering ~4π
- Detection efficiency ~ 80% @ 5 MeV
- Si detector for β

** J.C.Hardy et al., Phys. Lett. B, 71, 307 (1977)

TAS developed by the Valencia team (Spain, B. Rubio, J.L. Tain, A. Algora et al.) : Proceedings of the Int. Conf. For nuclear Data for Science and technology (ND2013)

TAS MEASUREMENTS @ JYVÄSKYLÄ UNIV. (JYFL)

- IFIC of Valencia (J.L. Tain et A. Algora et al.)

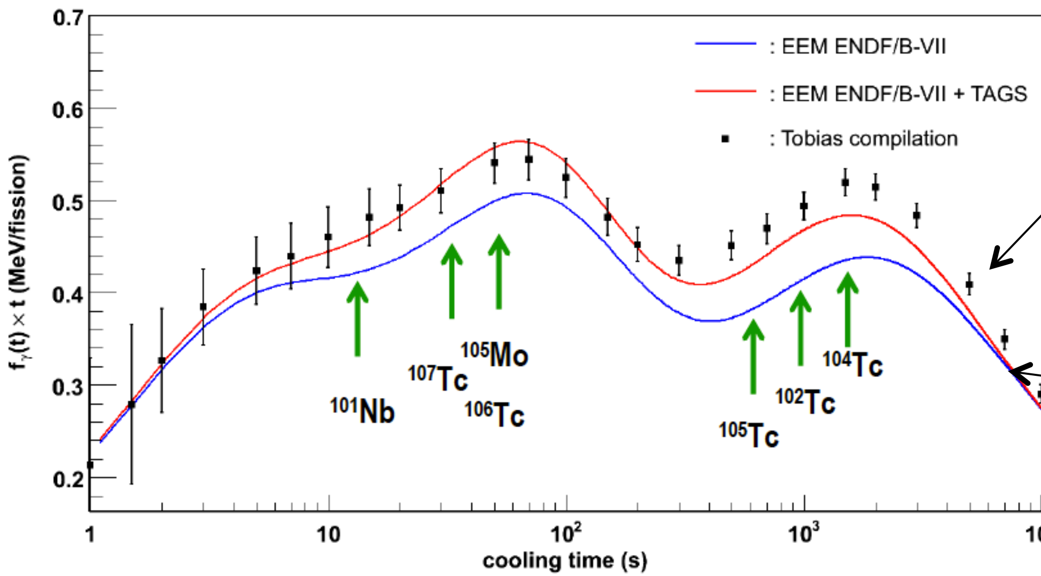
Reactor Decay Heat in ^{239}Pu: Solving the γ Discrepancy in the 4-3000-s Cooling Period,

Algora et al., Phys. Rev. Lett. 105, 202501 (2010),

D. Jordan, PhD thesis, Univ. Of Valencia 2010

⇒ Taking into consideration the TAS data of the $^{102;104\text{-}107}$Tc, ^{105}Mo, and ^{101}Nb isotopes measured @ Jyväskylä
⇒ i.e. correcting 5 nuclei out of 7 for the Pandemonium effect

Impact of the results for ^{239}Pu: electromagnetic component



Integral measurement of reference

Summation method calculations of the decay heat

D. Jordan, A. Algora et al. Phys. Rev. C 87, 044318 (2013)

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Back to the summation method for antineutrinos:

- the only one adapted to the computation of the antineutrino emission associated to various reactor designs (roadmap for IAEA) ;
- computation of antineutrino spectra for which no beta spectrum was measured ;
- off-equilibrium effects
- different binnings etc… for reactor neutrino experiment analyses (DC, DB, …)
- AND one of the only alternatives to ILL spectra !!!

⇒ **Update of summation method spectra for ^{235}U, ^{239}Pu, ^{241}Pu and ^{238}U with the latest published TAS data**

Summation Method: Ingredients

- $N_\beta\ (W) = K\ pW(W-W_0)^2\ F(Z,W)L_0(Z,W)C(Z,W)S(Z,W)G_\beta\ (Z,W)(1+\delta_{WM}W)$

Where $W=E/m_ec^2$, K = **normalization constant**,

$pW(W-W_0)^2$ = **phase space, to be modified if forbidden transitions**

$F(Z,W)$ = **Fermi function**

$L_0(Z,W)$ **and** $C(Z,W)$ = **finite dimension terms (electromagnetic and weak interactions)**

$S(Z,W)$ = **screening effect**

$G_\beta\ (Z,W)$ = **radiative corrections**

δ_{WM} = **weak magnetism term (the most uncertain one ! Cf. P. Huber, could change the normalization of the spectra if very different value…)**

- **Using Huber's prescriptions (formulae and values from PRC84,024617(2011)) + energy conservation for conversion into antineutrino spectrum, for each beta branch of each fission product**
- **Individual fission yields from the JEFF3.1 database are used**

Summation Method: Ingredients

- **In order to choose one specific nuclear decay database for one given nucleus, the order in which the bases are read is important: the first one in which the fission product is found is the chosen one:**

The **Greenwood TAS data set** (29 nuclei), the **experimental data measured by Tengblad et al.** (85 nuclei), experimental data from the evaluated nuclear databases: **JEFF3.1** (305, 345, 347, and 318 nuclei, respectively, for ^{235}U, ^{239}Pu, ^{241}Pu, and ^{238}U) **and JENDL2000** (61, 62, 61, and 58 nuclei, respectively), **Evaluated Nuclear Structure Data File nuclei** (94, 106, 109, and 97 nuclei respectively), **Gross theory spectra from JENDL** (214, 215, 227, and 221 nuclei, respectively), and the **"Q_β" approximation** for the remaining unknown nuclei (22, 32, 38, and 33 nuclei, respectively).

$\Rightarrow$ **810, 874, 896 and 841 fission products taken into account respectively**

- **Irradiation times with MURE: 12 h for ^{235}U, 1.5 days for $^{239;241}Pu$, and 450 days for ^{238}U.**

$\Rightarrow$ **Taking into consideration the latest published TAS data of the $^{102;104–107}Tc$, ^{105}Mo, and ^{101}Nb isotopes (A. Algora et al. Phys. Rev. Lett. 105, 202501 (2010)) ?**

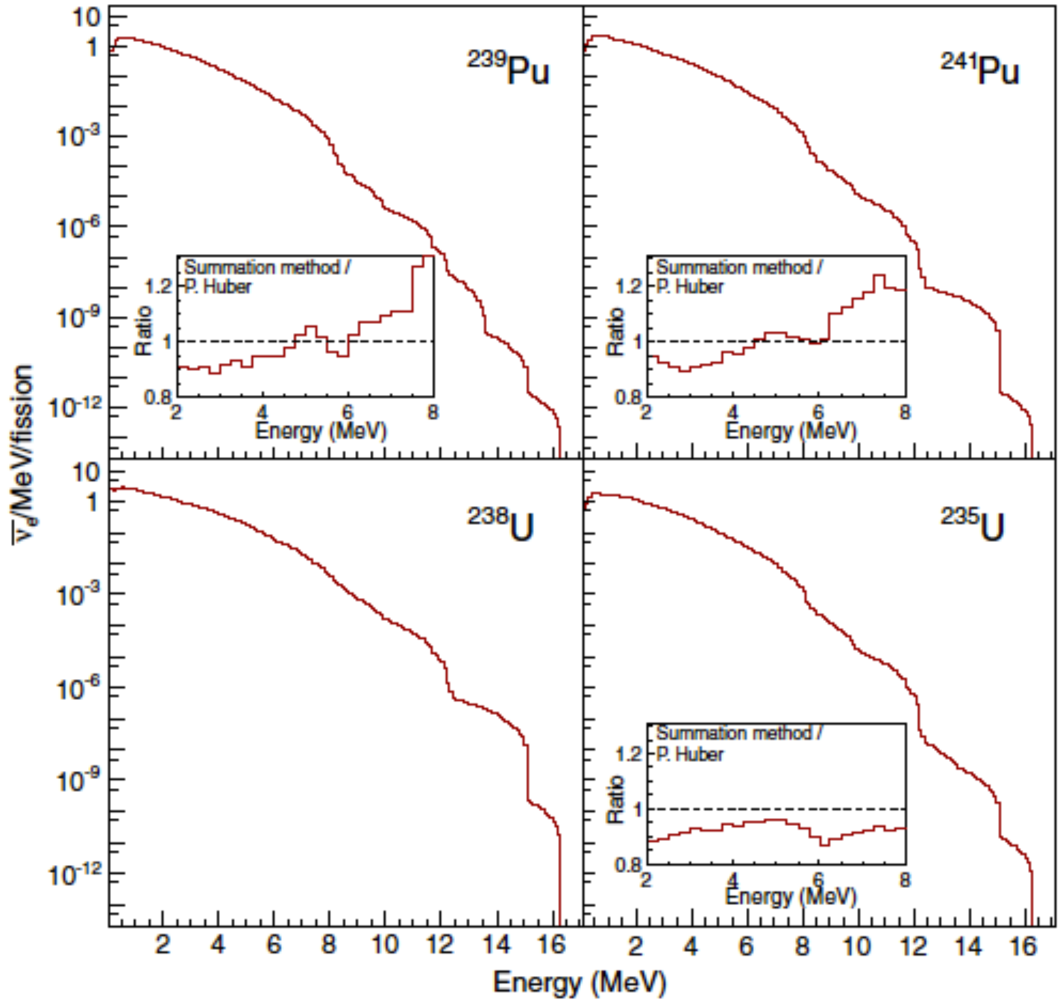
$\Rightarrow$ **i.e. correcting 5 nuclei out of 7 for the Pandemonium effect**

Inclusion of the latest TAS data in the Antineutrino Summation Spectra:

- **With the recently measured TAS data set by Algora et al. Phys. Rev. Lett. 105, 202501 (2010):**

Reconstructed antineutrino energy spectra, including the latest TAS data from Algora et al.

In the insets: ratios of the spectra to the ones computed by Huber PRC84,024617(2011) **converted reference spectra from ILL β-spectra**



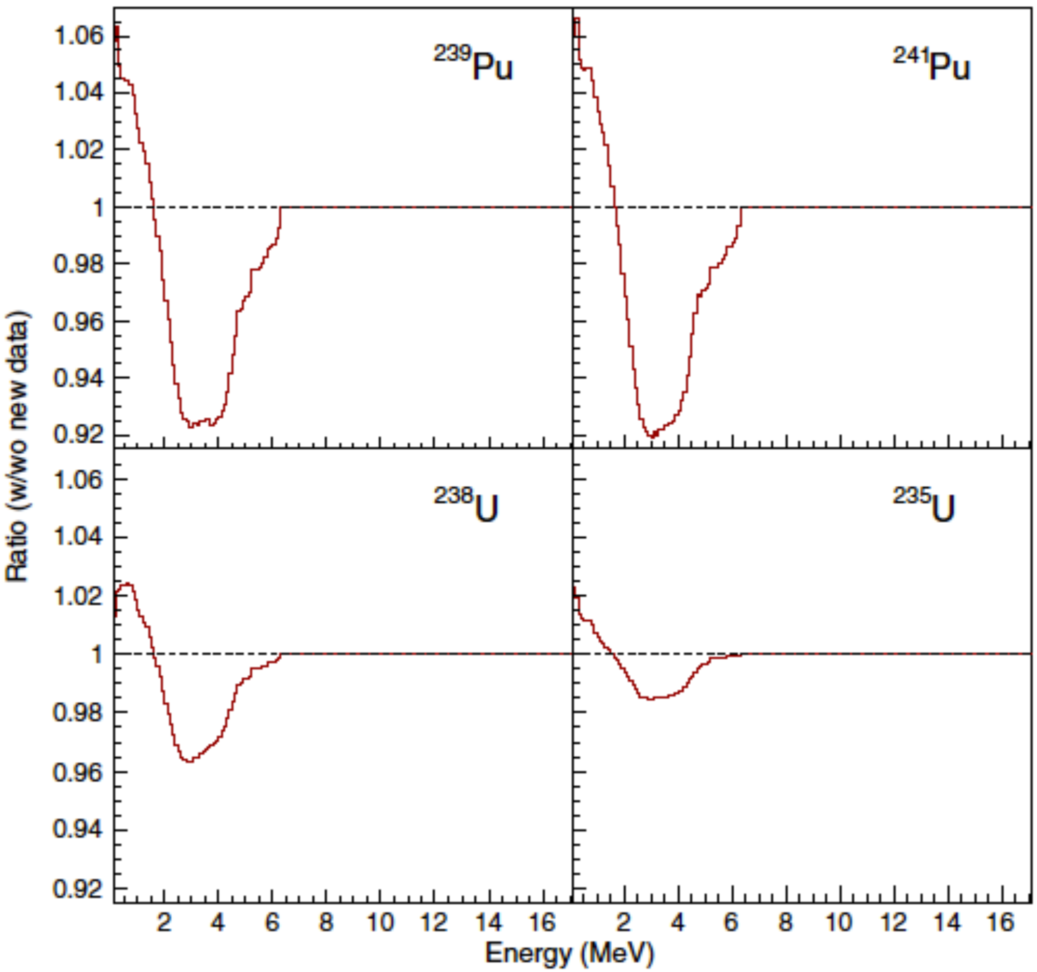
Subatech

Inclusion of the latest TAS data in the Antineutrino Summation Spectra:

Ratios of summation antineutrino spectra including the new TAS data for $^{102;104\text{–}107}$Tc, ^{105}Mo, and ^{101}Nb over the same spectra but with the JEFF3.1 data

- $^{239;241}$Pu energy spectra: noticeable deviation from unity observed in the 0–6 MeV energy range reaching an 8% decrease.
- ^{238}U energy spectrum: effect reaches a value of 3.5% at 2.5–3 MeV.
- ^{235}U: 1.5% at 2.5–3.5 MeV, expected since these nuclei are a small contribution to the ^{235}U spectrum.

Phys. Rev. Lett. 109, 202504 (2012)



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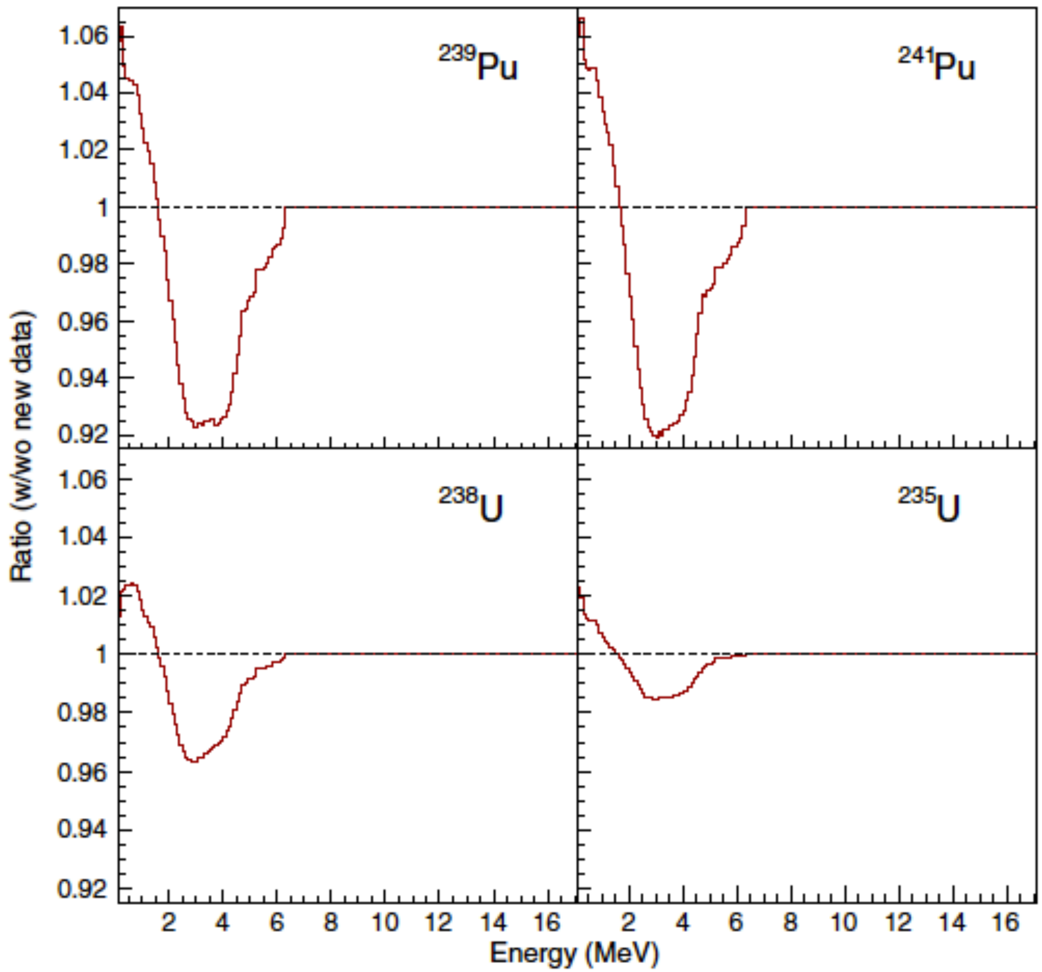

- $^{239;241}Pu$ energy spectra: noticeable deviation from unity observed in the 0–6 MeV energy range reaching an 8% decrease.
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⇒ Shows the important role of the Pandemonium nuclei in the $\bar{\nu}$ summation spectra
⇒ The summation spectra are among the only ways to estimate the antineutrino spectra independently from the still unique ILL integral β-spectra
⇒ New measurements required, list of nuclei identified

New measurements @JYFL (Jyväskylä,Finland)

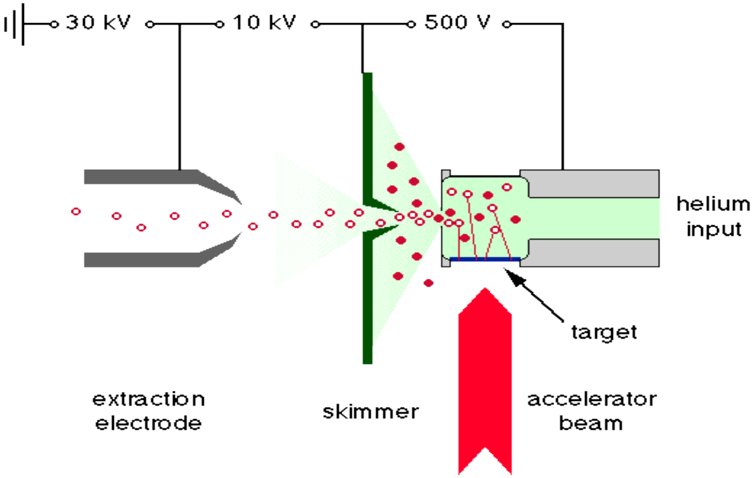
- 7 nuclei have been already measured at JYFL of Jyväskylä (Finland), analysis is on-going (A. Algora et al. Proc. of the Int. Conf. ND2013): Br and Rb
- Motivations: Decay Heat, Reactor Antineutrinos, Nuclear Structure, Nuclear Astrophysics

<u>PhD Thesis work</u>:

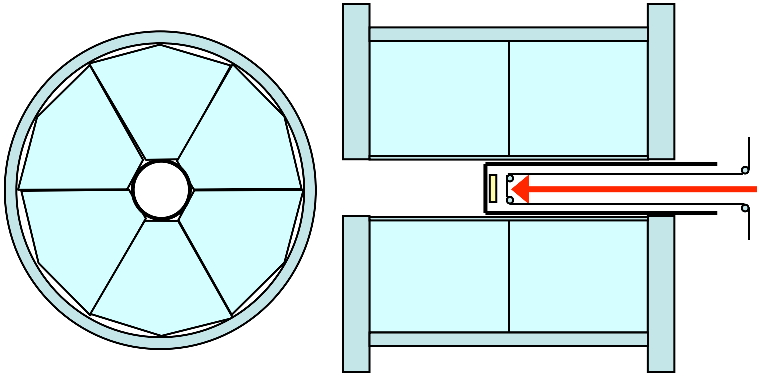
- E. Valencia (IFIC-Valencia)
- S. Rice (University of Surrey)
- Z. Issoufou (SUBATECH-Nantes)

<u>JYFL</u>: Good selection of the measured nucleus needed → IGISOL* + Penning trap JYFLTRAP**

*J.Ärje et al., NIM A 247,431 (1986)
**V.S.Kolhinen et al., NIM A 528,776 (2004)



Valencia-Surrey TAS



Among the future plans of the TAS collaboration related to Antineutrino Spectra:

Next experiments:

- Another 9 nuclei to be measured in Feb-March 2014 @ JYFL for antineutrinos, decay heat & Nuclear Structure (SUBATECH-IFIC proposal)

- Participation of the TAS collaboration to CHANDA Nuclear Data European Project, in the FP beta decay properties part ;

- Some nuclei of interest for antineutrinos are beta-n emitters: participation to the IAEA beta-n CRP: New experiments on Beta-n emitters will be proposed, of interest for neutrino physics, (& nuclear structure, reactor physics, nuclear astrophysics)

⇒ Next experiment proposal in preparation…

Outline

- Introduction
- Summation Method for Antineutrino Energy Spectrum
- On the Nuclear Data Side: Synergy with Decay Heat, Pandemonium Effect, Total Absorption Spectroscopy Technique
- New Reactor Antineutrino Spectra With the Summation Method
- Examples of Antineutrino Spectra required for Innovative Fuels and Reactors
- Conclusions and Outlooks

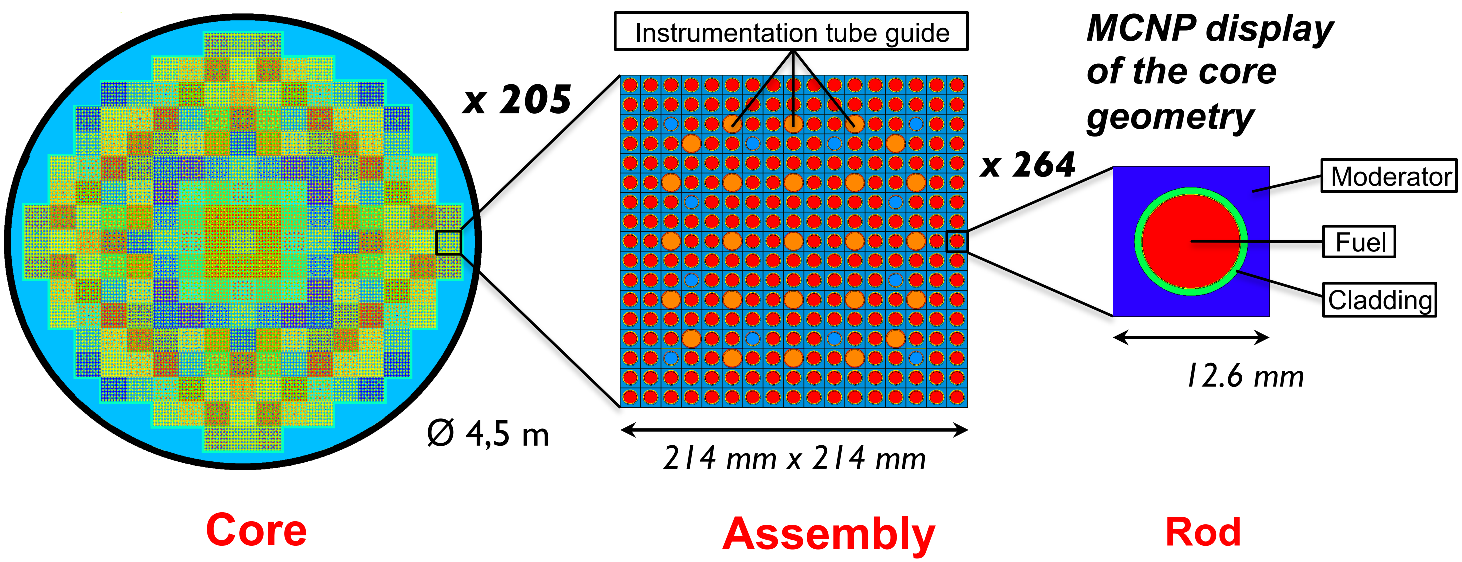
Reactor Modelling and Simulation

Determine feasibility of remote monitoring of various reactor designs and operations using an antineutrino detector:

- all parameters influencing the neutron energy distribution in the core may influence the antineutrino emission

⇒ Detailed reactor core model is required in order to get realistic results

⇒ Detailed study adapted to each design, dynamics vs core at equilibrium, uncertainties…



- **Method:** choice of Monte-Carlo codes for their ability to: model complex geometry, continuous treatment of energy, thermal and fast neutron spectra… BUT memory limited.
- MURE code: Monte-Carlo coupled to evolution code, and nuclear databases => summation method antineutrino energy spectra associated to reactor models

Scenarios and reactors of interest for IAEA ?

- PWRs
- BWR, FBR, CANDU reactors
- Research reactor / isotope production reactors Pth >10MWth
- Future reactors (PBMRs, Gen IV reactors, ADS, especially reactors using carbide, nitride, metal or molten salt fuels, advanced CANDUs...)
- MOX Management, Innovative fuels

UOx, MOX, ThUOx, PuOx, thermal neutron spectrum

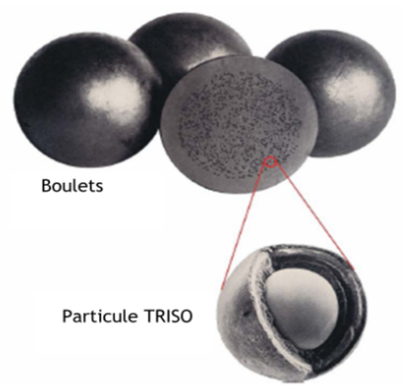
$^{238}U/^{239}Pu$ or $^{232}Th/^{233}U$ cycles, fast neutron spectrum

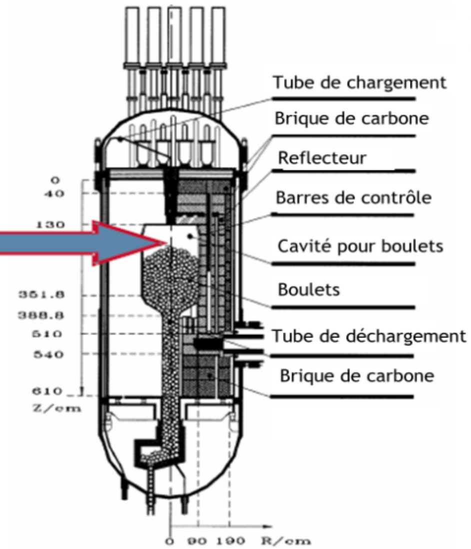
Minor Actinides, Protected Plutonium Production fuel…

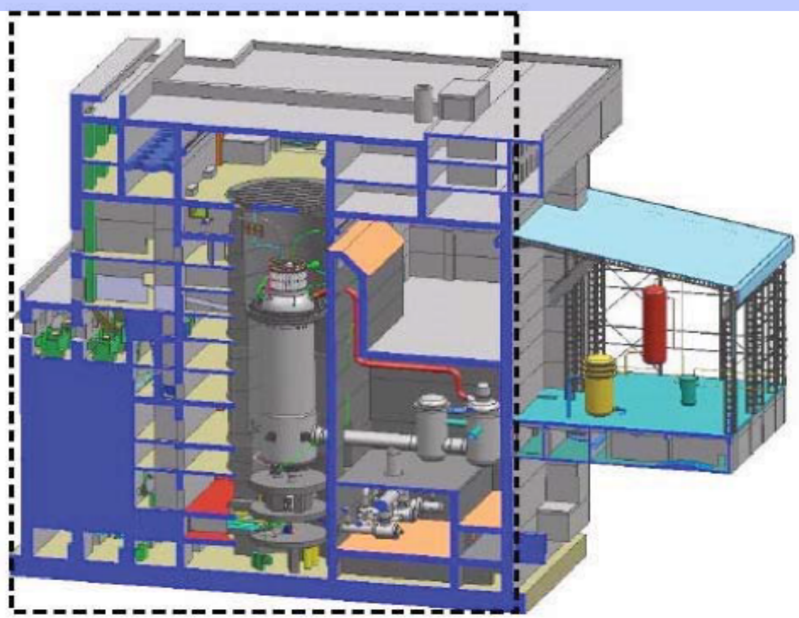
Pebble Bed Reactor

Pebble Bed Reactor: Very High Temperature Reactor
Power of few 100s MWth

- **-Power generation**
- **-Hydrogen production**
- **-Desalination**







Concept developed in South Africa with various changes
Demonstrators on operation in China and Japan

S. Cormon PhD thesis
http://tel.archives-ouvertes.fr/tel-00825082

« Double heterogeneity » problem
stochastic distributions of CPs in pebbles [1] and of pebbles in-core.

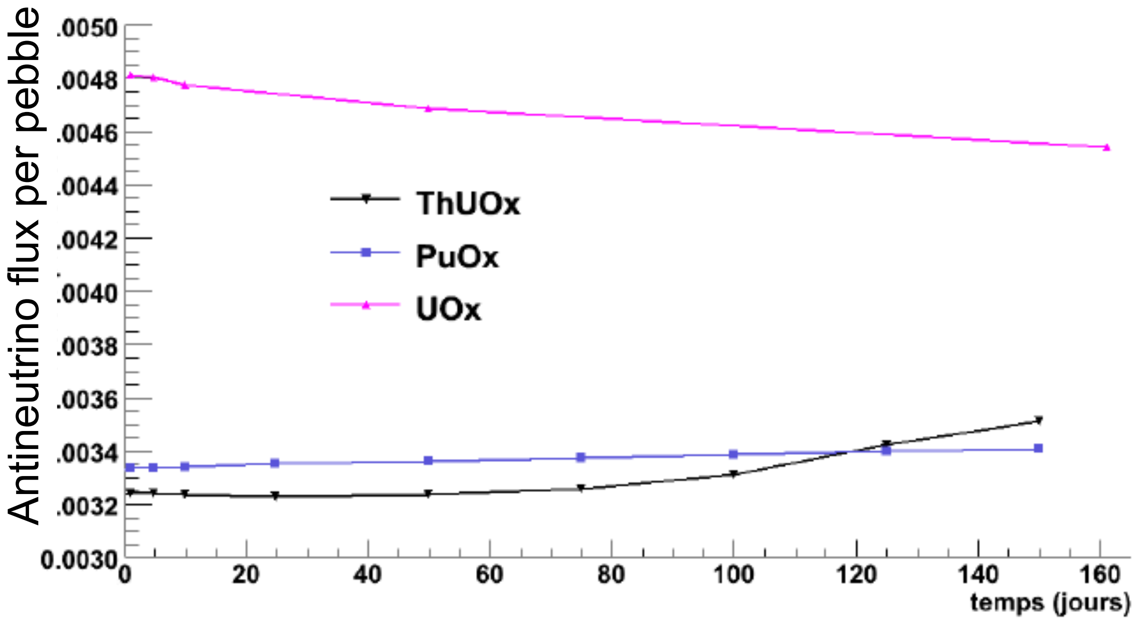
[1] E. BOMBONI et al. *Nuclear Science and Engineering*, Vol. 162, p. 282-298 (2009).

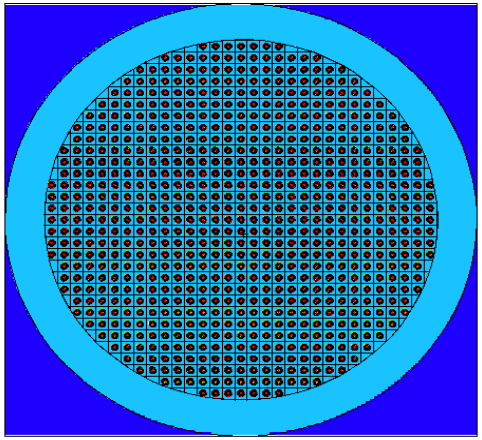
Pebble Bed Reactor

PBR of 200MWth[1]

359548 pebbles containing each 15000 Coated Particles

Fuels : UOx (enriched 8.2%), ThUOx, PuOx.





MCNP view geometry

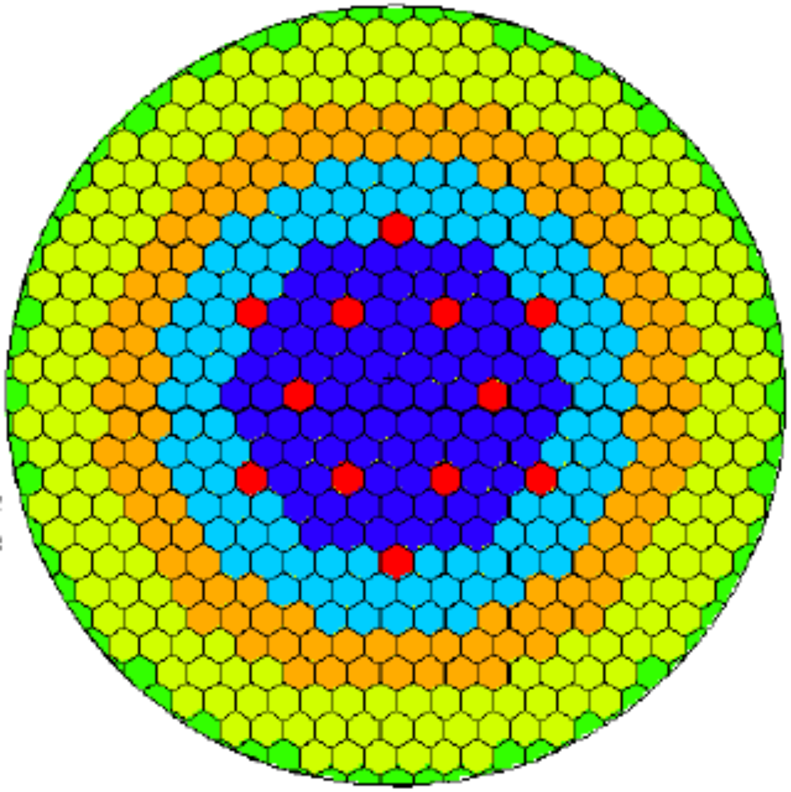
Detected flux in a 1t liq. Gd-loaded scint. antineutrino detector, 50% det. Efficiency

30% discrepancy between UOx and ThUOx or PuOx fluxes

[1] Results of a Benchmark Considering a High-temperature Reactor (HTR) Fuelled with Reactor-grade Plutonium, OECD/NEA Nuclear Science Committee Working Party on the Physics of Plutonium Fuels and Innovative Fuel Cycles,ISBN 978-92-64-99007-4.

Na- Fast Breeder Reactor

FULL REACTOR SIMULATION

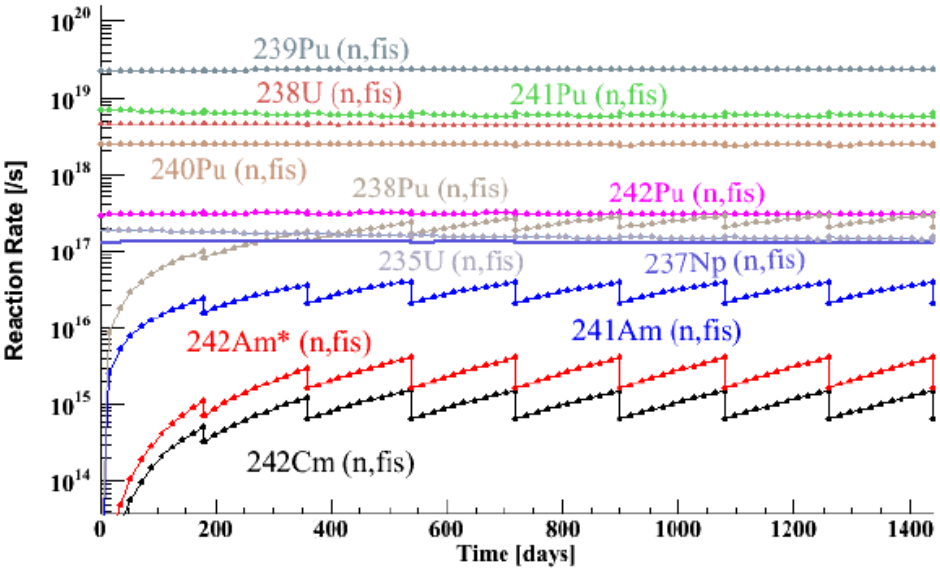


1250MWth - refuelling every 180 days
sodium-cooled
Inner core: 21% Pu, refuelled 1/3
Exterior core: 28% Pu, refuelled 1/3
Radial Blanket: MA, refuelled 1/8
Axial Blanket: MA, refuelled 1/3

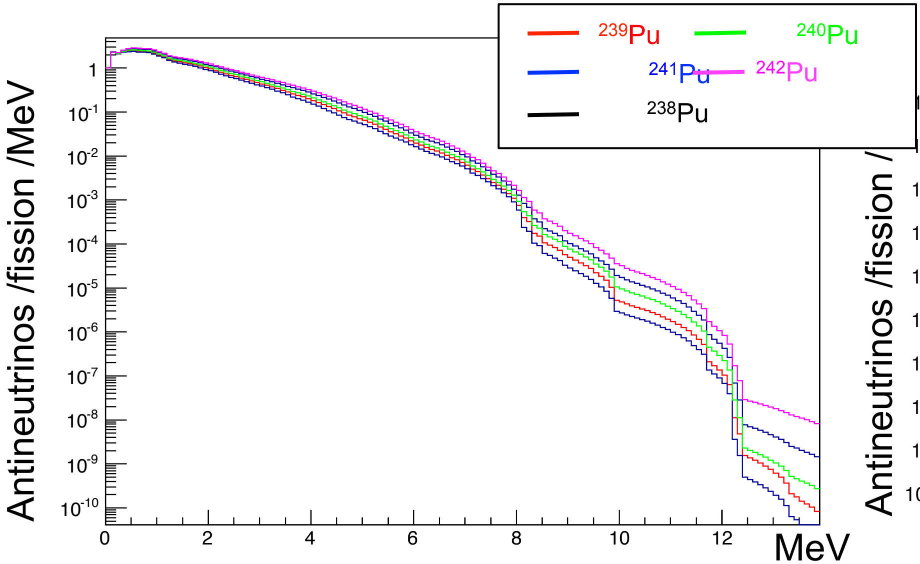
Simul of reactor start-up and 8 first cycles

Reactor physics x-checks:
- effective transmutation of Minor Actinides
- delayed neutron fraction OK

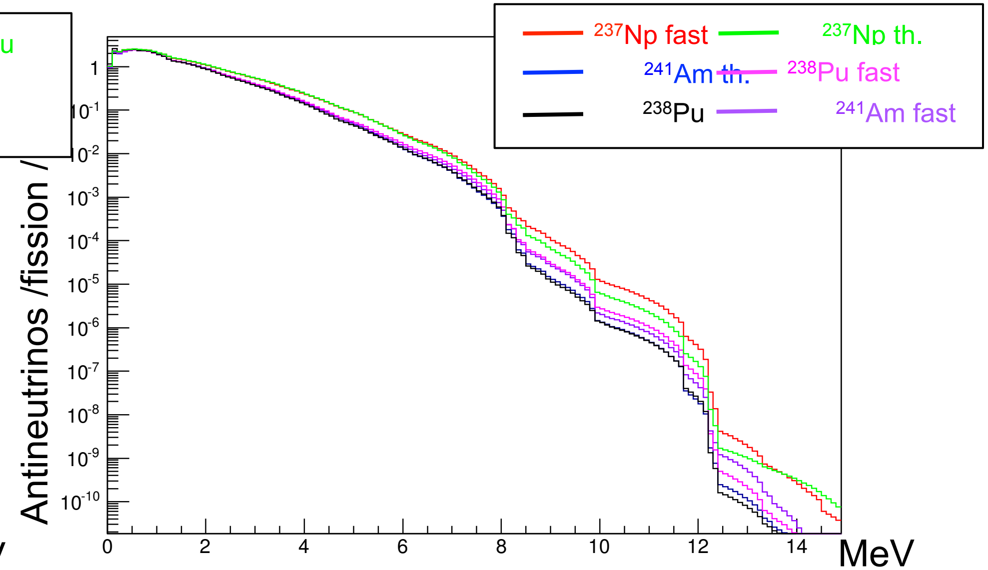
Na-Fast Breeder Reactor



Several compositions of the blankets can be studied



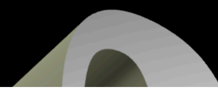
Example of Minor Actinides (MA) composition of the blankets



Summation Method antineutrino spectra needed for this case: fast fission from all Pu isotopes, fast fission Minor Actinides, fast fission ^{235}U, …

Conclusions & Outlooks

- The ILL data are still the only and most precise measurements, considered as a reference in neutrino physics + Newly converted ν spectra => normalization shift w.r.t previous ν spectra => « reactor anomaly »
- Independent evaluations of the reactor spectra could provide new constraints on the existence of light sterile neutrinos. A possible alternative = spectra built with the summation method
- Pandemonium nuclei play a major role in the estimate of the antineutrino spectra using the summation method and TAS measurements of these nuclei could allow us to improve drastically the predictiveness of these spectra.
- Interest for Nuclear Data: new experiment planned in Feb.-March 2014 to measure another 9 nuclei selected for their importance in antineutrino energy spectra + synergy with decay heat, reactor physics, nuclear structure and astrophysics
- Interest for safeguards: ESARDA WG + IAEA Ad-Hoc WG;
- A substantial part of the nuclei at the origin of the antineutrinos are predicted by macroscopic models => need for microscopic model predictions + for comparisons with measurements



And the TAS Collaboration

J. Agramunt[1], A. Algora[1], J. Äystö[4], M. Bowry[3], V.M. Bui[2], R. Caballero-Folch[6], D. Cano-Ott[5], V. Eloma[4], T. Eronen[4], E. Estévez[1], M. Fallot[2], G. F. Farrelly[3], A. Garcia[5], W. Gelletly[3], M. B. Gomez-Hornillos[6], V. Gorlychev[6], J. Hakala[4], A. Jokinen[4], M.D. Jordan[1], A. Kankainen[4], F.G. Kondev[7], T. Martínez[5], E. Mendoza[5], F. Molina[1], I. Moore[4], A.Porta[2], A. Pérez[1], Zs. Podolyák[3], H. Penttilä[4], P. H. Regan[3], S. Rice[3], J. Rissanen[4], B. Rubio[1], J.L. Taín[1], E. Valencia[1], C. Weber[4] + IGISOL people

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THANK YOU