LA STRUCTURE NUCLEAIRE POUR L'ASTROPHYSIQUE ET LES APPLICATIONS : PHYSIQUE DES NEUTRINOS ET DES REACTEURS

M. Fallot, SUBATECH, Nantes, France

CSI IN2P3 26 octobre 2017
sur les activités ISOL en France

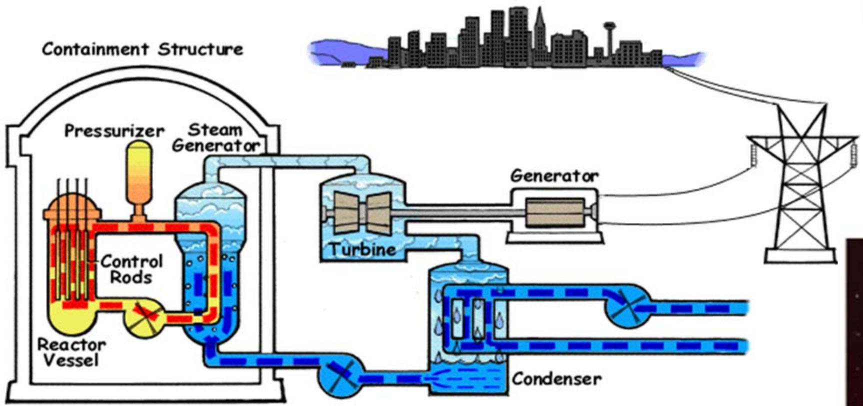
Outline

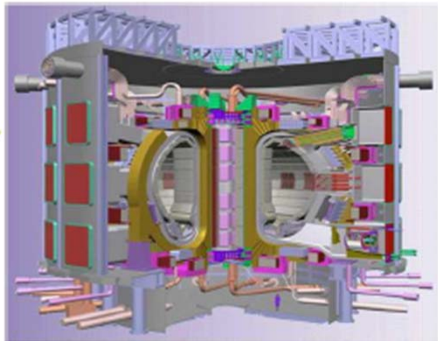
- Introduction
- Nuclear structure for astrophysics :
  - ❑ rp-process
  - ❑ core-collapse SN
  - ❑ r-process
- Nuclear structure for neutrino and reactor physics :
  - ❑ Fission products β-decay
  - ❑ Pandemonium problem in the nuclear data
  - ❑ Decay Heat
  - ❑ Reactor antineutrinos & reactor anomaly
- Societal impact : nuclear data (fission product decay data masses with AME)
- Links with theory & modelisation in nuclear astrophysics, neutrino and reactor physics

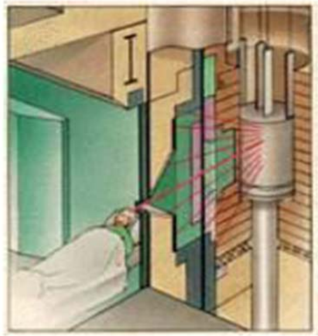
Nuclear Structure for ...

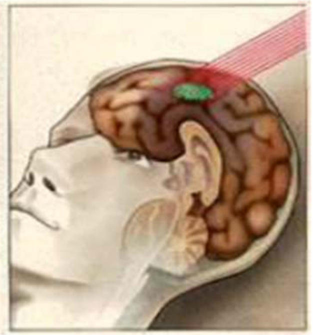
Nuclear fission energy
Nuclear fusion research
Radiation protection
Nuclear medicine
(Nuclear) security

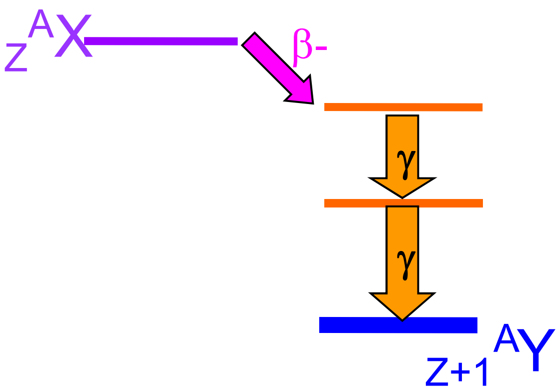
Object and materials analysis
Astrophysics
Basic science

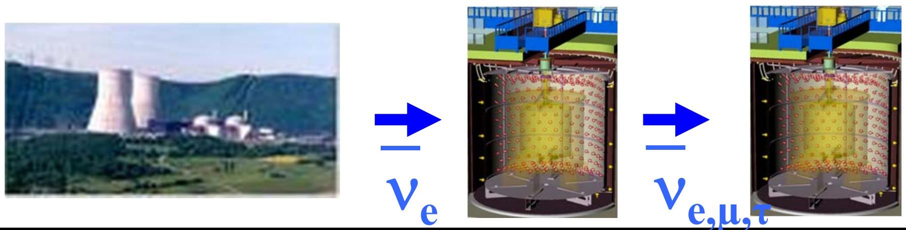












DOUBLE CHOOZ

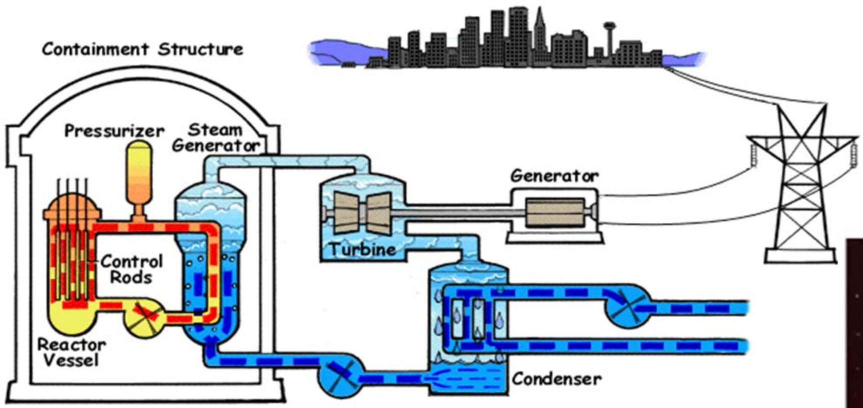
Cf. A. Plompen (CEE) @ PND2 [redacted]

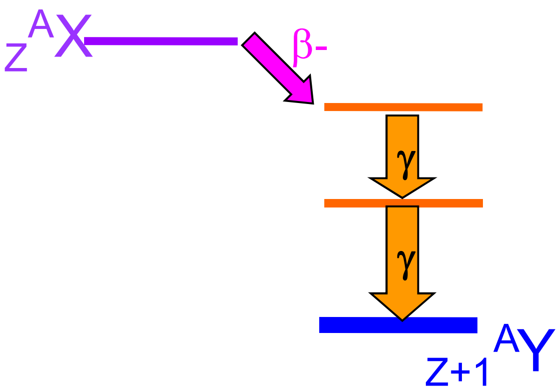
[redacted]

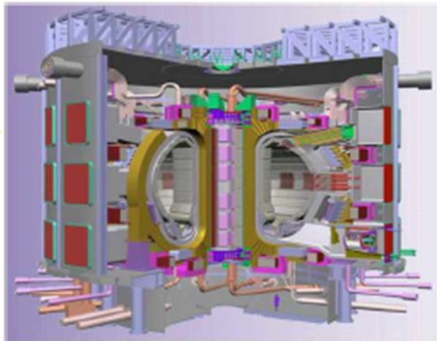
Nuclear Structure for … with ISOL beams

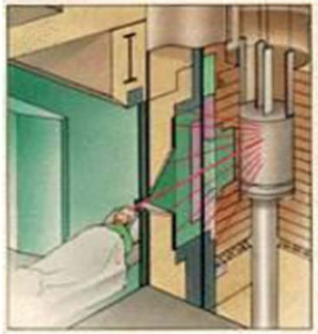
Nuclear fission energy
Nuclear fusion research
Radiation protection
Nuclear medicine
(Nuclear) security

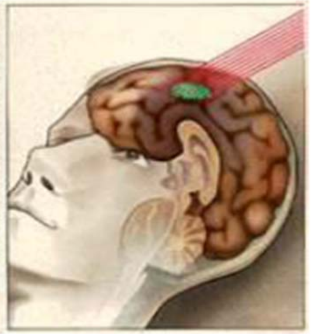
Object and materials analysis
Astrophysics
Basic science



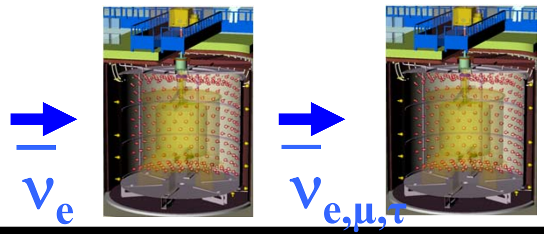








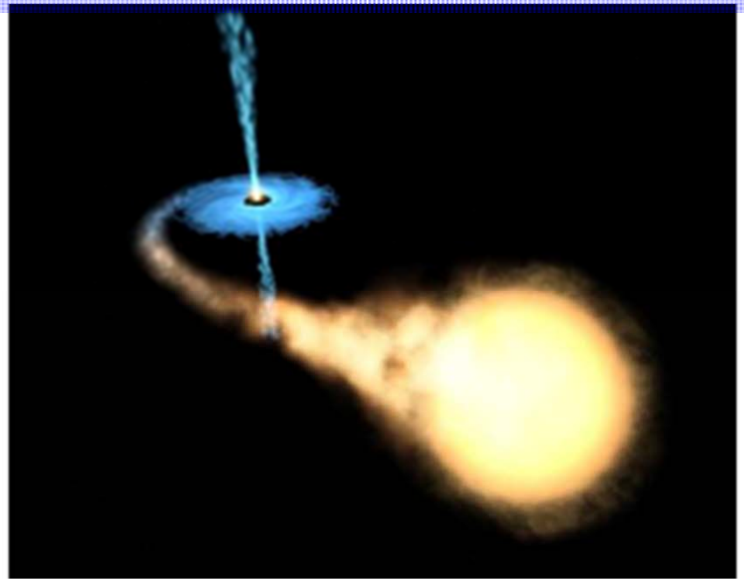
Nuclear Power Station



Near detector Far detector

Cf. A. Plompen (CEE) @ PND2 workshop, CEA-DAM Oct. 2014

Explosive Nucleosynthesis



- Which processes power the light curves of X-ray bursts ?
- What are the explosion mechanisms of Supernovae ?

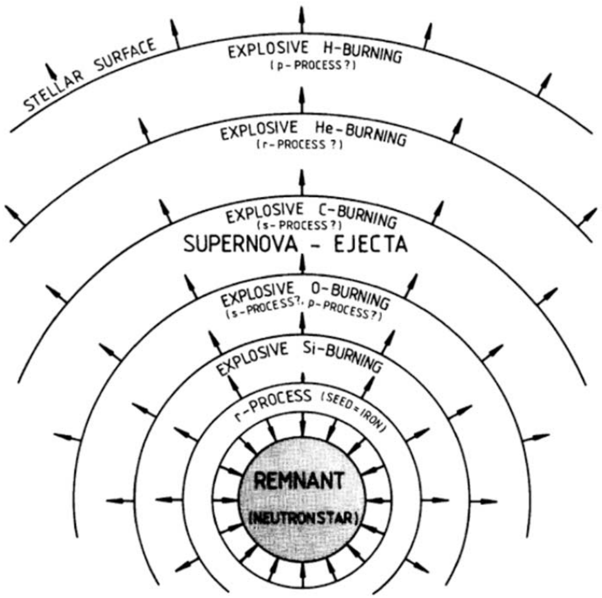


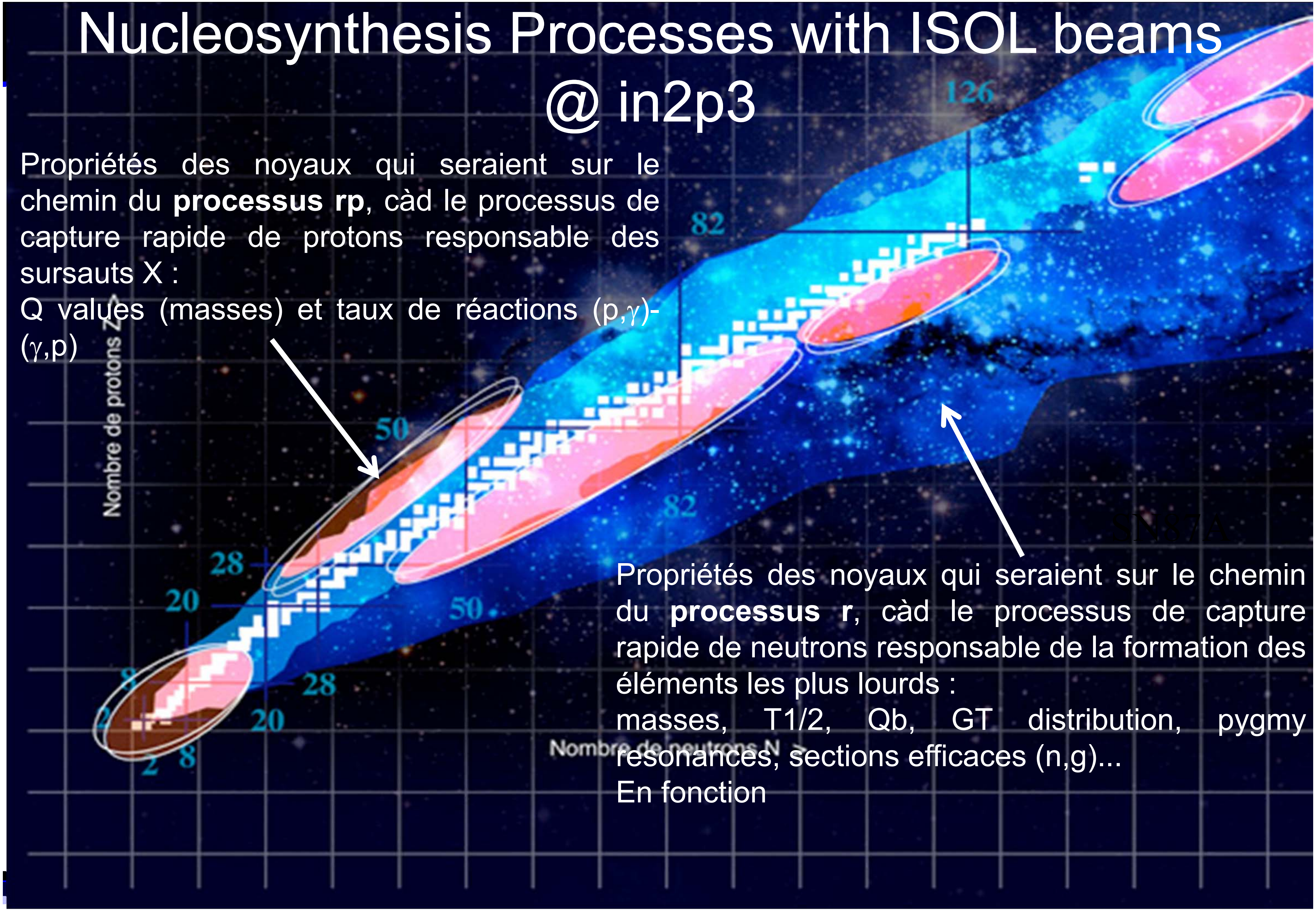
FIGURE 8.12. Schematic diagram of an exploding massive star with a collapsing core (the remnant) and various explosive burning shells in the supernova ejecta.

- Origin of heavy elements?
- Constitution of neutron stars ?

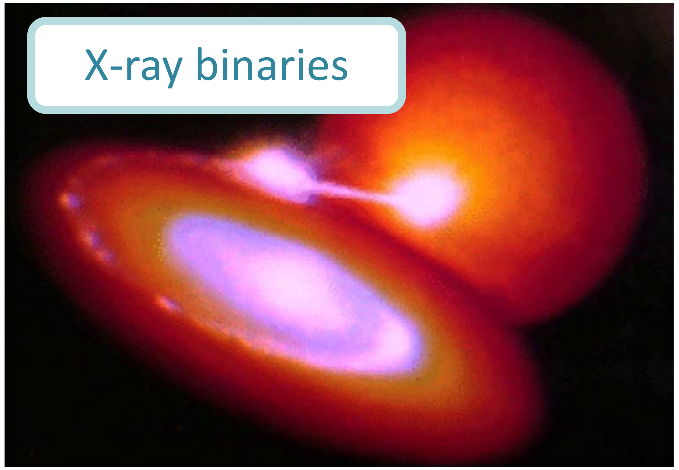
Nucleosynthesis Processes with ISOL beams @ in2p3

Propriétés des noyaux qui seraient sur le chemin du **processus rp**, càd le processus de capture rapide de protons responsable des sursauts X :
Q values (masses) et taux de réactions (p,γ)-(γ,p)

Propriétés des noyaux qui seraient sur le chemin du **processus r**, càd le processus de capture rapide de neutrons responsable de la formation des éléments les plus lourds :
masses, T1/2, Qb, GT distribution, pygmy resonances, sections efficaces (n,g)...
En fonction



Rp-process with S^3/SPIRAL1



S^3-LEB (Z<=54)

Complementarity of SPIRAL1 beams below ^{78}Y

Sequence of rapid proton captures and β+ decays near the proton dripline

Type I XRB
(masses to be constrained)

Nuclide	Mass excess [174] (keV)	Purpose
^{26}P	#10973 ± 196	W
^{27}S	#17543 ± 202	W
^{31}Cl	−7067 ± 50	W
^{43}V	#−18024 ± 233	W
^{45}Cr	−18965 ± 503	W
^{46}Mn	#−12370 ± 112	W
^{47}Mn	#−22263 ± 158	W
^{51}Co	#−27274 ± 149	W
^{56}Cu	#−38601 ± 140	W
^{61}Ga	−47090 ± 53	W
^{62}Ge	#−42243 ± 140	T
^{66}Se	#−41722 ± 298	T
^{70}Kr	#−41676 ± 385	T
^{71}Br	−57063 ± 568	T
^{83}Nb	−58959 ± 315	T
^{84}Nb	#−61879 ± 298	T
^{86}Tc	#−53207 ± 298	T
^{89}Ru	#−59513 ± 503	W
^{90}Rh	#−53216 ± 503	W
^{96}Ag	#−64571 ± 401	T
^{97}Cd	#−60603 ± 401	T
^{99}In	#−61274 ± 401	W
^{103}Sn	#−66974 ± 298	T

A. Parikh arXiv:1211.5900v1

Mass measurements along N=Z with PILGRIM

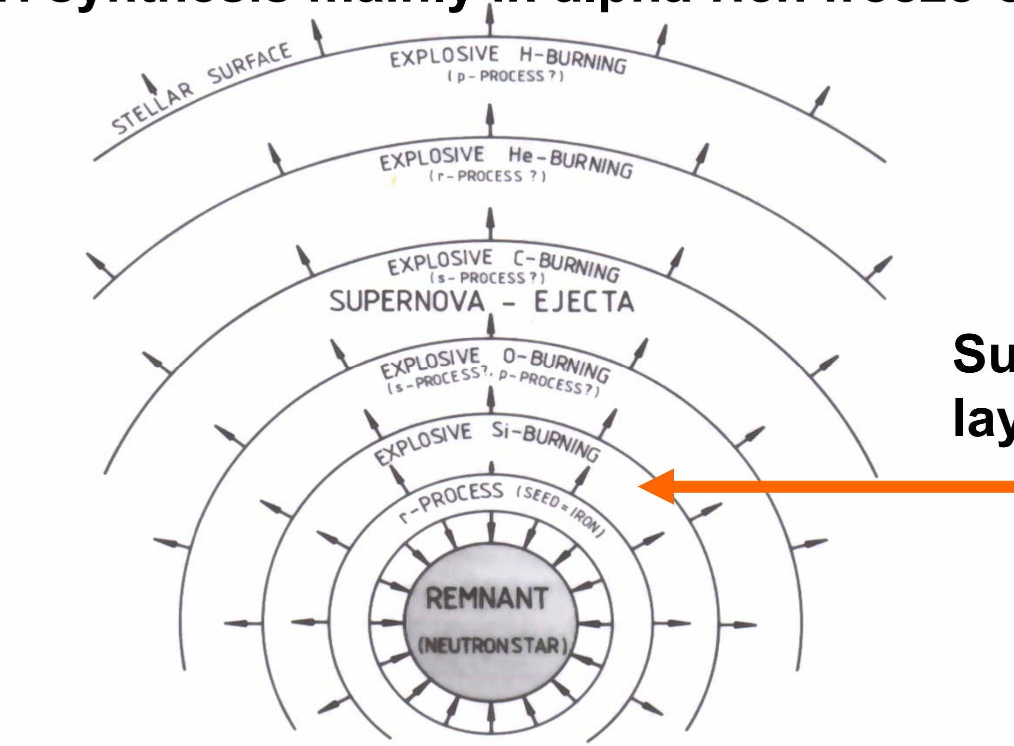
MR-TOF-MS ΔM~50keV
Puis DESIR ΔM~10keV
Program starting in 2020 (SPIRAL1 + S^3-LEB): only S^3 will provide access to the most exotic nuclei + refractory elements (ex.: ^{80}Zr, ^{87}Tc, ^{64}Ge, ^{48,49}Fe)

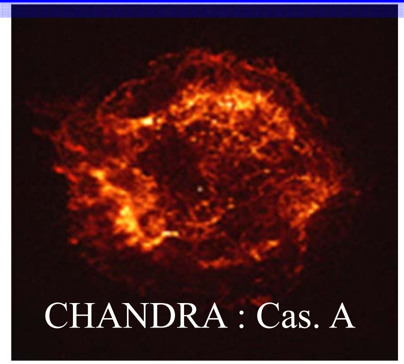
See P. Delahaye & D. Lunney's presentations

Coll: CENBG, IPNO, CSNSM, GSI, KU Leuven, JYFL

^{44}Ti Nucleosynthesis

^{44}Ti synthesis mainly in alpha-rich freeze-out :





Supernova shock passing through Si layers of progenitor star

Alpha-rich Freeze-out

T≈ 5.10^9K, ρ≈10^7 g/cm^3
Nuclei dissociate into nucleons and alpha particles

Expansion and cooling : nuclei reassemble under quasi-nuclear statistical equilibrium
Abundances of nuclei in local equilibrium with their neighbours
Expansion => T drops => **local eq. broken,** new abundance pattern, numerous α-particles remain => α capture chains such as : ^{28}Si(α,γ)^{32}S(α,γ)^{36}Ar(α,γ)^{40}Ca(α,γ)^{44}Ti

⇒ **^{44}Ti production rate** : probes the **innermost shells** of the explosion
⇒ **Sensitive to :** explosion energy, neutron excess, position of the mass-cut, explosion asymmetry, nuclear reaction cross-sections.

^{44}Ti Nucleosynthesis

Quest for resonances in the reaction ^{45}V(p,γ)^{46}Cr

Proposal E773 : Á. M. Sánchez Benítez, J.-C. Thomas et al.

TABLE 5

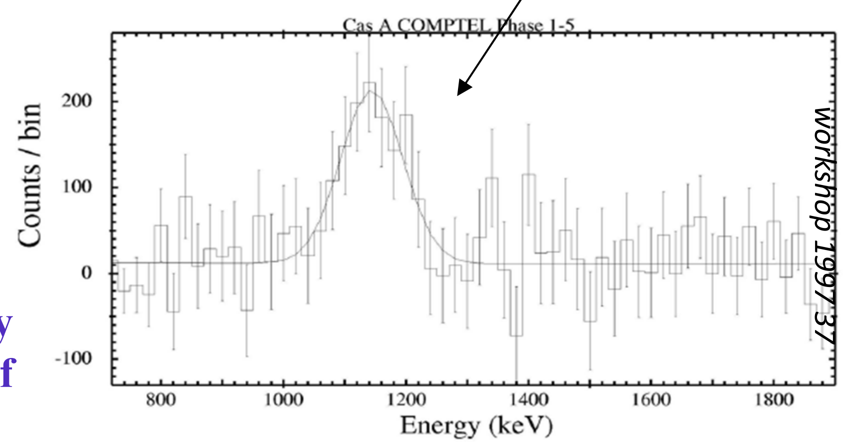
ORDER OF IMPORTANCE OF REACTIONS PRODUCING ^{44}Ti AT $\eta = 0$[a]

Reaction	Slope
^{44}Ti(α, p)^{47}V	−0.394
α(2α, γ)^{12}C	+0.386
^{45}V(p, γ)^{46}Cr	−0.361
^{40}Ca(α, γ)^{44}Ti	+0.137
^{57}Co(p, n)^{57}Ni	+0.102
^{36}Ar(α, p)^{39}K	+0.037
^{44}Ti(α, γ)^{48}Cr	−0.024
^{12}C(α, γ)^{16}O	−0.017
^{57}Ni(p, γ)^{58}Cu	+0.013
^{58}Cu(p, γ)^{59}Zn	+0.011
^{36}Ar(α, γ)^{40}Ca	+0.008
^{44}Ti(p, γ)^{45}V	−0.005
^{57}Co(p, γ)^{58}Ni	+0.002
^{57}Ni(n, γ)^{58}Cu	+0.002
^{54}Fe(α, n)^{57}Ni	+0.002
^{40}Ca(α, p)^{43}Sc	−0.002

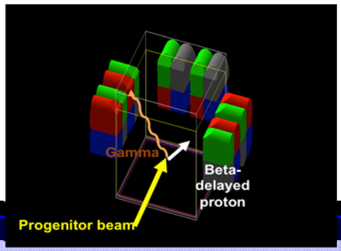
[a] Order of importance of reactions producing ^{44}Ti at $\eta = 0$ according to the slope of $X(^{44}\mathrm{Ti})$ near the standard reaction rates.

- ^{44}Ti is produced in type II supernovae (SN II) mechanism: α-rich freeze-out. Shock-wave after core-collapse reaches the α-rich region in the cooling phase, $1 < T_9 < 5$
- ^{44}Ti ($T_{1/2}$= 59 y) is a cosmic gamma ray emitter (67.9, 78.4, 1157 keV). Observed by COMPTEL and INTEGRAL satellites
- **^{44}Ti ejecta is a sensitive probe for core-collapse models**
- ^{44}Ti main responsible for ^{44}Ca solar system abund.

Abundance of produced ^{44}Ti is **very sensitive to the reaction rate of ^{45}V(p,γ) (not known exp.)**



Iyudin et al. 2nd INTEGRAL workshop 1997 37



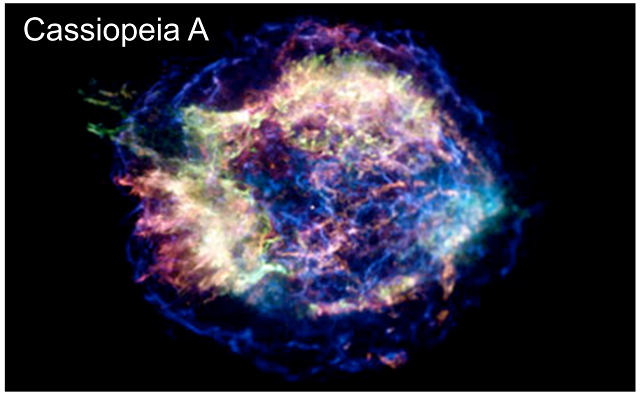
Spectroscopy of key nuclei in astrophysics by beta-delayed proton emission: ^{46}Mn

Experimental goal: quest of resonances, including branchings, in daughter nucleus

Experimental approach: Beta-delayed proton emission studied with ACTAR TPC & EXOGAM @ LISE/GANIL, and then with Spiral1/S^3

Study of core-collapse supernovae

masses around ^{78}Ni (JYFL)



Credit: NASA

Core-Collapse Supernovae simulation :
One of the BIG astro challenges

Present best 3D hydro simulations do not yet produce satisfactory CCSN explosion **=>** **Microphysics is essential !**

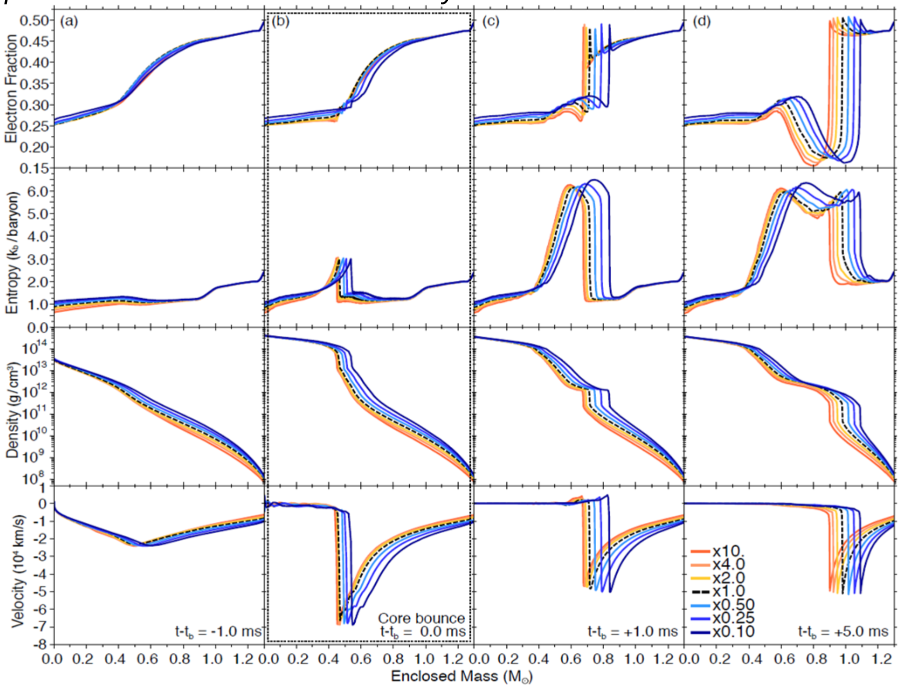
Key observables

- **EC rates : GT response** (β-decay, charge exchange)
- **Nuclear mass**
- **EoS**

Key regions of the nuclear chart

- **Around ^{78}Ni (N=50)**
- **Around ^{128}Pd (N=82)**

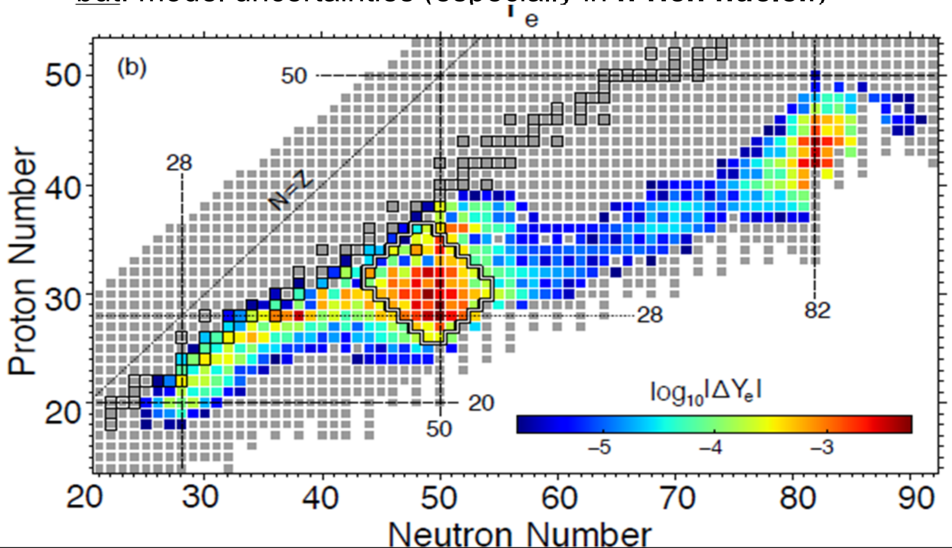
position of the shock front is extremely sensitive to the nuclei EC rates



Sullivan *et al.* ArXiV:1508.0734

Electron-capture rates

- EC : crucial all along the life of a star
  (particularly in massive stars → CCSN!)
- <u>but</u>: model uncertainties (especially in **n-rich nuclei**!)



Sullivan *et al.* ArXiV:1508.0734

B. Bastin, A. Kankainen (experiment) / F. Gulminelli, A. Fantina (theory) et al.

Study of core-collapse supernovae

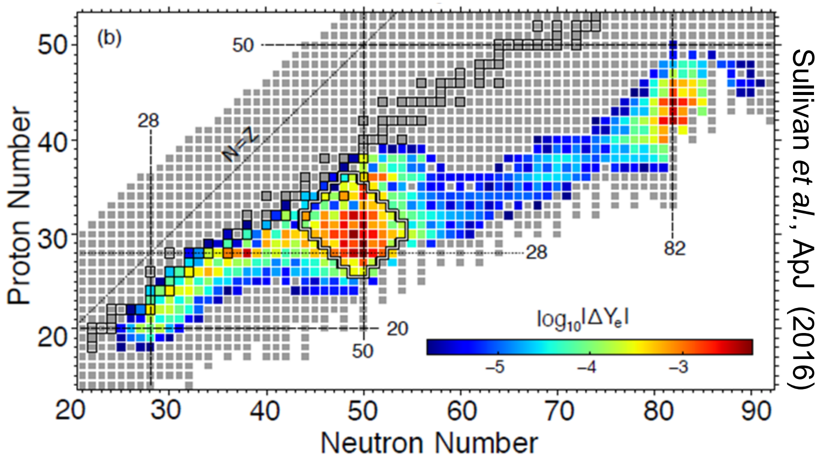
masses around ^{78}Ni (JYFL)

- **Precise mass measurements (< ~100 KeV) required for the computation of:**
  - **Q value in EC rates**
  - **+ EoS of asymmetric matter**

  = inputs to theoretical model developed by the LPC Caen group

- **Key exotic nuclei around N=50 (^{78}Ni) and N=82 (^{128}Pd) -> linked to shell effects**

⇒ Accepted experiment: mass measurements around ^{78}Ni @ JYFL (2017):
^{67,68}Fe, ^{68,69,70,71}Co, ^{74,75}Ni, ^{76,77,78,79}Cu, ^{81,82}Zn, ^{84}Ga, ^{79}Ge, ^{78}As and ^{84}Br *(GANIL PhD)*



Most relevant nuclei regarding EC rates (collapse phase)

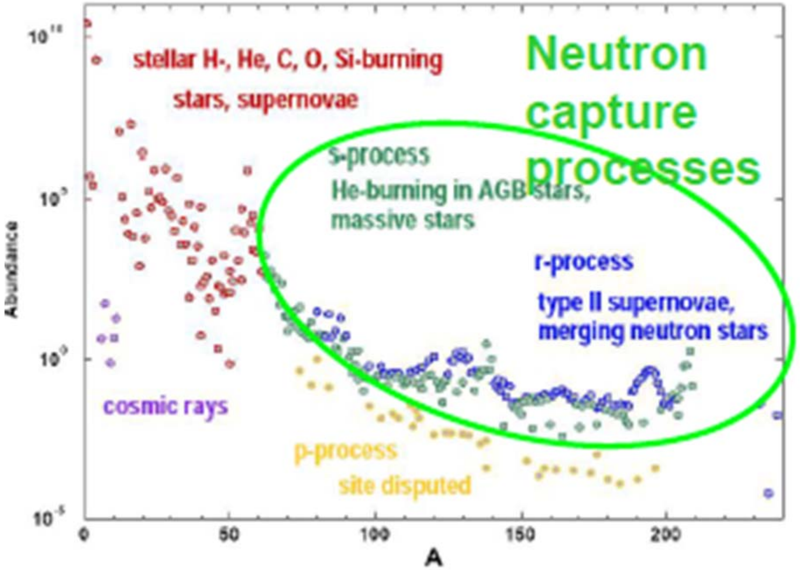
PhD thesis of S. Giraud (astrophysics) and L. Canete (nuclear structure)

=> In a second step, study GT strength distributions for key nuclei

Coll: LPC Caen, IPNL, IPNO, CENBG, JYFL, IFIN-HH, LUTH, KU Leuven

R-Process

R-process: A short and very high neutron flux produces very neutron-rich nuclei in a short time, which then decay to stability, responsible for half the elements heavier than iron in the Universe



- Nn >> 10^{20} cm^{-3}
- T ~ 10^{9} K (?)
- t ~ 1 s

The conditions are such that the $\tau_\beta > \tau(n,\gamma)$ & $\tau(\gamma,n)$ --> the nuclear flow goes deep into the exotic n-rich region

1. Astrophysics aspects:

- Parametric models: "canonical" site-independent models
- **"Realistic" models: Supernova explosion: ν-driven wind**

Decompression of initially-cold neutron star matter

BUT THE ASTROPHYSICS SITE REMAINS UNKNOWN !!!

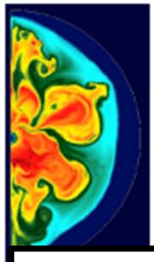
2. Nuclear Physics aspects:

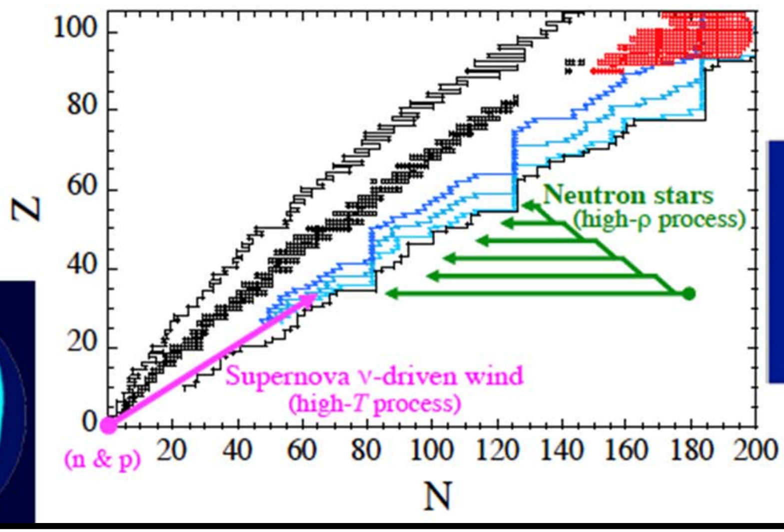
- *Neutron captures*
- Photodisintegration rates
- *Beta-decays (T1/2, masses, Gamow-Teller strength, Pn, …)*
- Fission (neutron-induced, β-delayed, spontaneous) rates
- ν-nucleus interaction rates

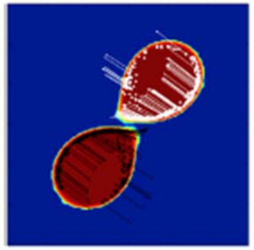
for ~5000 exotic neutron-rich (experimentally unknown) nuclei !!!

R-Process

one of the still unsolved puzzles in nuclear astrophysics
… the r-process site remains unknown …





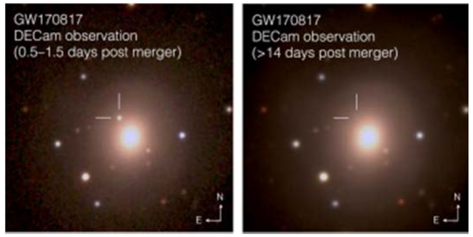


Our understanding of the r-process nucleosynthesis, i.e. the origin of about half of the nuclei heavier than Fe in the Universe is considered as one of the top 11 questions in Physics and Astronomy

(“Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century”: 2003, National research council of the national academies, USA)

The Astrophysical Journal Letters, 848:L16 (7pp), 2017 October 20
https://doi.org/10.3847/2041-8213/aa9059

The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. I. Discovery of the Optical Counterpart Using the Dark Energy Camera



Kilonova predicted by astronuclear physicists Metzger et al. in 2010 !!!

« Both the light curves and spectra closely **resemble predictions for a ‘kilonova’ a transient powered by radioactive decay of heavy nuclei and isotopes synthesized through the r-process in the merger ejecta**. This is the **first clear demonstration that r-process nucleosynthesis occurs in neutron star binary mergers,** and although this is a single event, the inferred ejecta mass and event rate suggest that such mergers could be the dominant r-process site. »

Impact of Mass Measurements on r-process

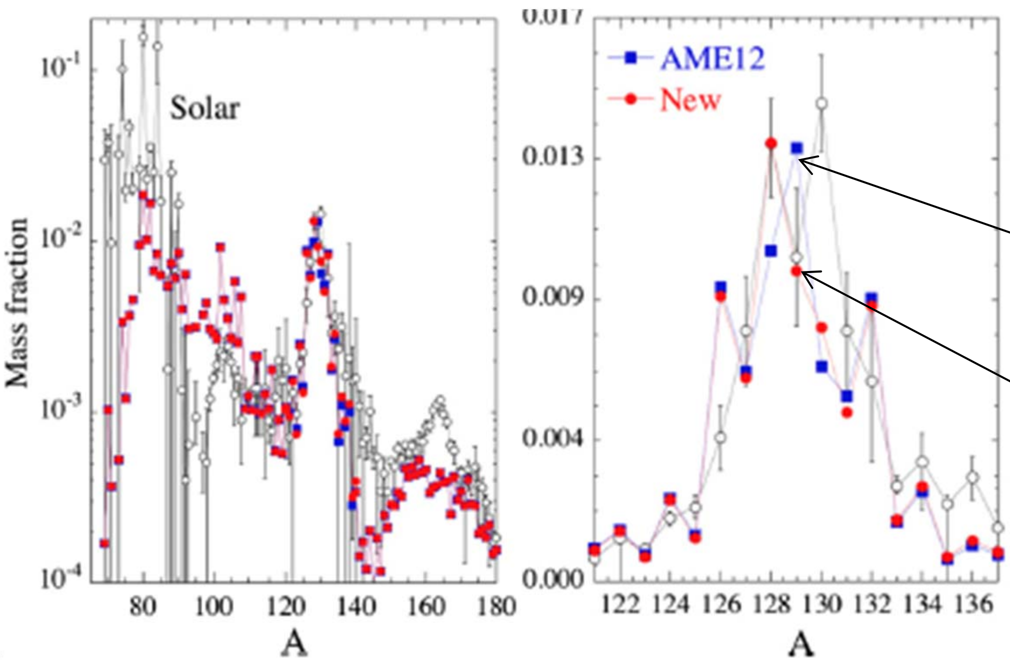
PRL 115, 232501 (2015) PHYSICAL REVIEW LETTERS week ending 4 DECEMBER 2015

Precision Mass Measurements of $^{129-131}$Cd and Their Impact on Stellar Nucleosynthesis via the Rapid Neutron Capture Process

D. Atanasov,[1] P. Ascher,[1] K. Blaum,[1] R. B. Cakirli,[2] T. E. Cocolios,[3] S. George,[1] S. Goriely,[4] F. Herfurth,[5] H.-T. Janka,[6] O. Just,[6] M. Kowalska,[7] S. Kreim,[1,7] D. Kisler,[1] Yu. A. Litvinov,[1,5] D. Lunney,[8] V. Manea,[8] D. Neidherr,[5] M. Rosenbusch,[9] L. Schweikhard,[9] A. Welker,[10] F. Wienholtz,[9] R. N. Wolf,[1] and K. Zuber[10]

Masses of $^{129-131}$Cd were determined with high precision using the Penning-trap mass spectrometer ISOLTRAP.

« Given the large volume of data required for r-process calculations, it is remarkable that only three masses make an observable impact on the predicted abundances, highlighting the importance of precision measurements in this region of the nuclear chart. »



Calculated distributions of the r-process abundance pattern obtained with a BH-NS merger scenario.
Blue squares: AME12 (complemented with HFB-24 masses for experimentally unknown isotopes) and corresponding rates,
Red circles: include the new Cd masses

β-decay of delayed neutron emitters as a "surrogate" of the (n,γ) reaction

J.L. Tain et al., PRL 115, 062502 (2015)

Enhanced γ-Ray Emission from Neutron Unbound States Populated in β Decay

J. L. Tain,[1,*] E. Valencia,[1] A. Algora,[1] J. Agramunt,[1] B. Rubio,[1] S. Rice,[2] W. Gelletly,[2] P. Regan,[2] A.-A. Zakari-Issoufou,[3] M. Fallot,[3] A. Porta,[3] J. Rissanen,[4] T. Eronen,[4] J. Äystö,[5] L. Batist,[6] M. Bowry,[2] V. M. Bui,[3] R. Caballero-Folch,[7] D. Cano-Ott,[8] V.-V. Elomaa,[4] E. Estevez,[1] G. F. Farrelly,[2] A. R. Garcia,[8] B. Gomez-Hornillos,[7] V. Gorlychev,[7] J. Hakala,[4] M.D. Jordan,[1] A. Jokinen,[4] V. S. Kolhinen,[4] F. G. Kondev,[9] T. Martínez,[8] E. Mendoza,[8] I. Moore,[4] H. Penttilä,[4] Zs. Podolyák,[2] M. Reponen,[4] V. Sonnenschein,[4] and A. A. Sonzogni[10]

(%)	$\Sigma I_{\beta n}=P_n$	$\Sigma i_{\beta\gamma}=P_\gamma$ (TAS)
^{87}Br	2.60(4)	3.5(5)
^{88}Br	6.58(18)	1.59(30)
^{93}Rb	1.39(7)	0.69(?)
^{94}Rb	10.18(24)	0.53(30)

^{94}Rb: γ-ray branching one order of magnitude higher than H-F calculation with standard parameters.

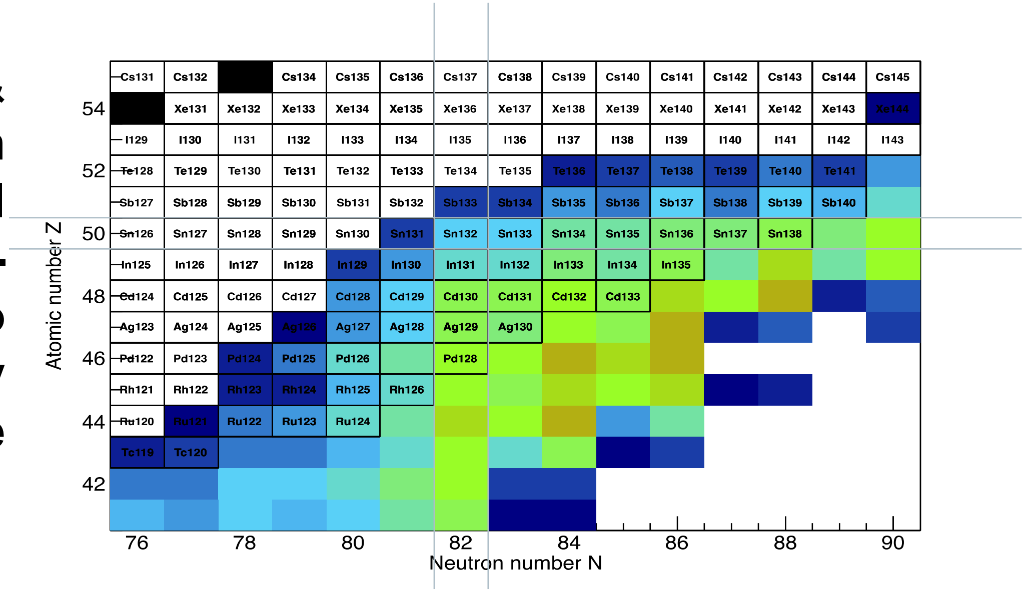
⇒ **Such an enhancement of Γγ will have a similar effect on the (n,γ) cross section: impact on r-process abundance**

⇒ Experiment done using the Total Absorption γ-ray Spectroscopy (TAGS) technique (calorimetry), the most suited for detection of high energy gamma rays

⇒ **Very interesting as (n,γ) reaction rates are very hard to measure on such exotic nuclei**

TAGS proposal and LoI @ ALTO

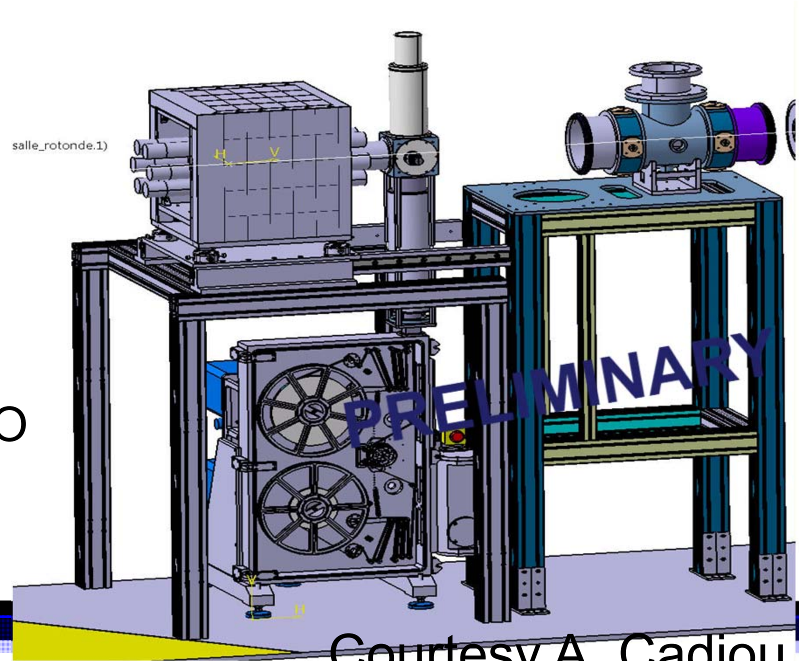
- A **proposal** with nuclear structure & astrophysics motivations accepted **(in 2014!!**) and experiment delayed to fall 2018: **Sn and In isotopes close to r-process paths + the first to propose to use beta-decay to populate pygmy resonances in exotic nuclei (influence r-process path(s), [Goriely PLB 1998])**



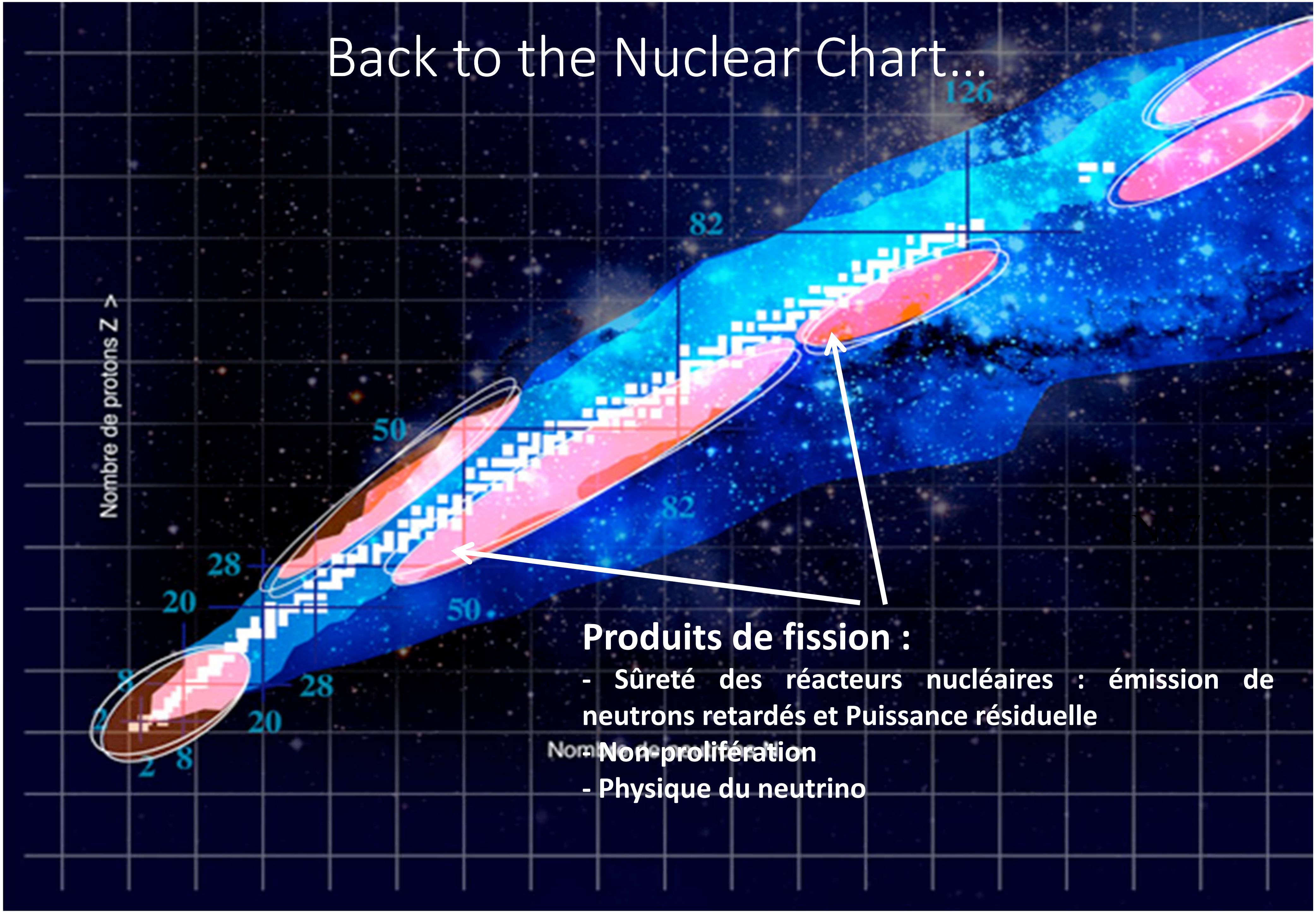
- **LoI** accepted on nuclei with **motivations for reactor neutrino calculations, decay heat and reactor control.**

- Most of the proposed nuclei are **β-n emitters**

Subatech Physics Case
\+ Mechanics for TAGS @ ALTO
\+ CeBr3 ancillary detector:

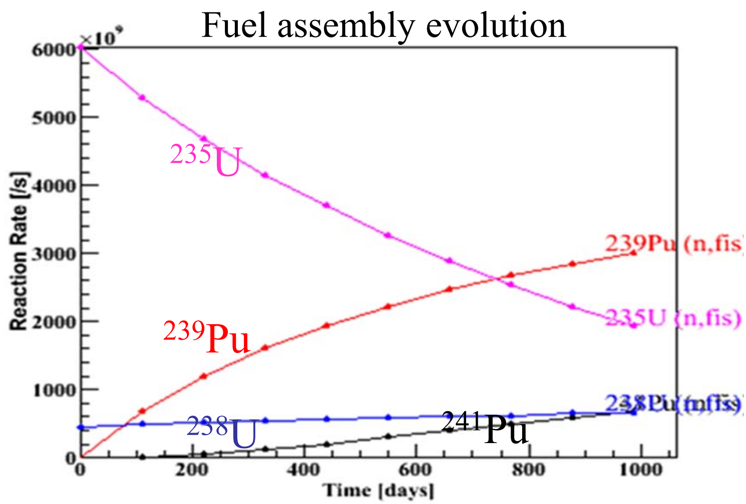


See D. Verney's presentation for Pn & high resolution spectroscopy measurements @ ALTO


Back to the Nuclear Chart…
Nombre de protons Z >
126
82
50
28
20
8
2
Produits de fission :
- Sûreté des réacteurs nucléaires : émission de neutrons retardés et Puissance résiduelle
- Non-prolifération
- Physique du neutrino

Reactors and Beta Decay

- In Pressurized Water Reactors, thermal power mainly induced by 4 isotopes:
  - ^{235}U and ^{238}U in fresh fuel
  - Other fissile nuclei (^{239}Pu & ^{241}Pu) created after reactor start by fission/capture process
  - Burn-up effect => unit GWd/t



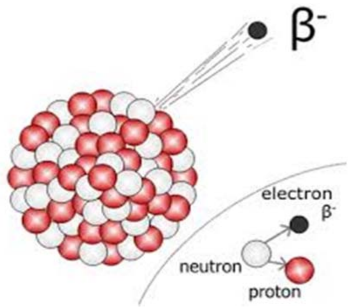
- Fission process gives thermal energy:

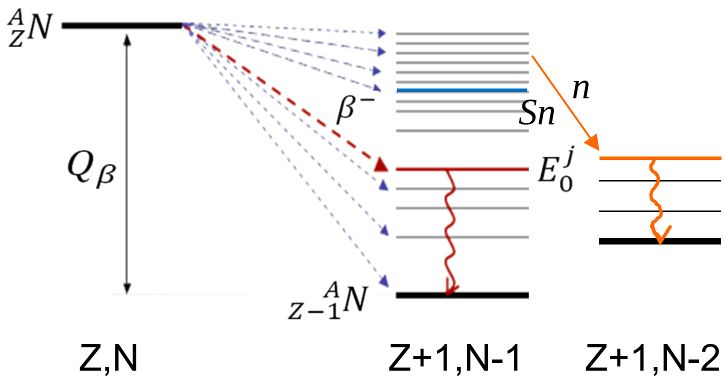
$$n + {}^{235}U \rightarrow {}^{236}U^{*} \rightarrow \mathrm{FP1} + \mathrm{FP2} + \mathrm{neutrons}\,(200MeV)$$

- The fission products (FP) after the fissions are neutron-rich nuclei undergoing β and β-n decays:

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

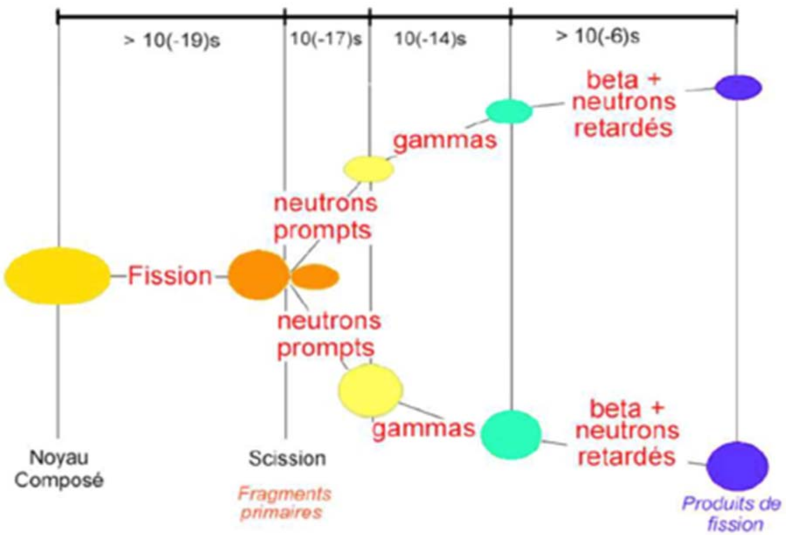
$$ {}^{A}_{Z+1}Y^{*} \rightarrow {}^{A}_{Z+1}Y + \gamma s $$





Beta Decay for Present and Future Reactors

- The exploitation of the products of the beta decay is threefold:
  - ❑ The released γ and β contribute to the "**<u>decay heat</u>**" → critical for reactor safety and economy
  - ❑ The **<u>antineutrinos</u>** escape and can be detected → reactor monitoring, potential non-proliferation tool and essential for fundamental physics
  - ❑ β-n emitters: **<u>delayed neutron fractions</u>** → important for the operation and control of the chain reaction of reactors



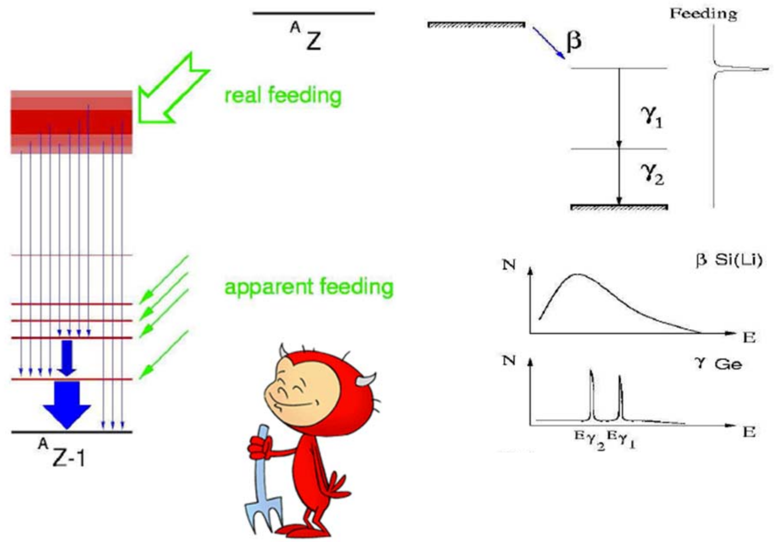
γ Measurement Caveat

- Before the 90s, conventional detection techniques: high resolution γ-ray spectroscopy
  - Excellent resolution but efficiency which strongly decreases at high energy
  - Danger of overlooking the existence of β-feeding into the high energy nuclear levels of daughter nuclei (especially with decay schemes with large Q-values)
- Incomplete decay schemes: overestimate of the high-energy part of the FP β spectra
- Phenomenon commonly called « pandemonium effect** » by J. C Hardy in 1977

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

➡ Strong potential bias in nuclear data bases and all their applications

Picture from A. Algora



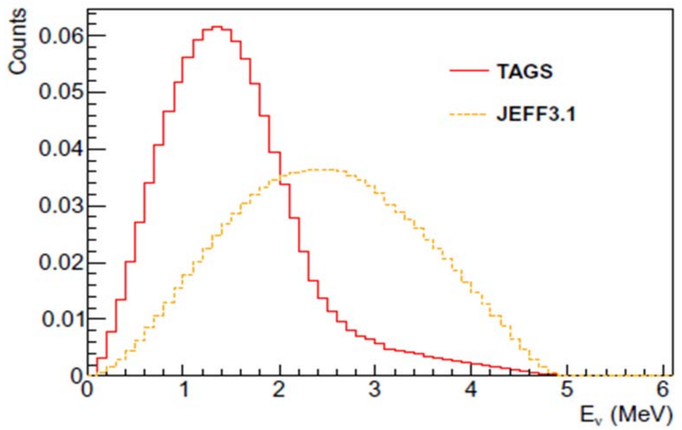


FIG. 1. Illustration of the pandemonium effect on the ^{105}Mo nucleus anti-ν energy spectrum presents in the JEFF3.1 data base and corrected in the TAS data.

Reactor Decay Heat (DH)

- **Definition:** following the shut-down of the chain reaction in a reactor, **the nuclear fuel continues to release energy called decay heat.**
- Evaluation of the **reactor safety** as well as **various economic aspects** of nuclear power
- **Emitters: essentially made up of FP and actinides**
  - DH: residual power of **6-12% of the nominal power** of the reactor just after its shut-down

- Estimate through **the only predictive method** for future reactors: **the « summation method »**

⇒ Summation of all the fission product and actinide contributions:

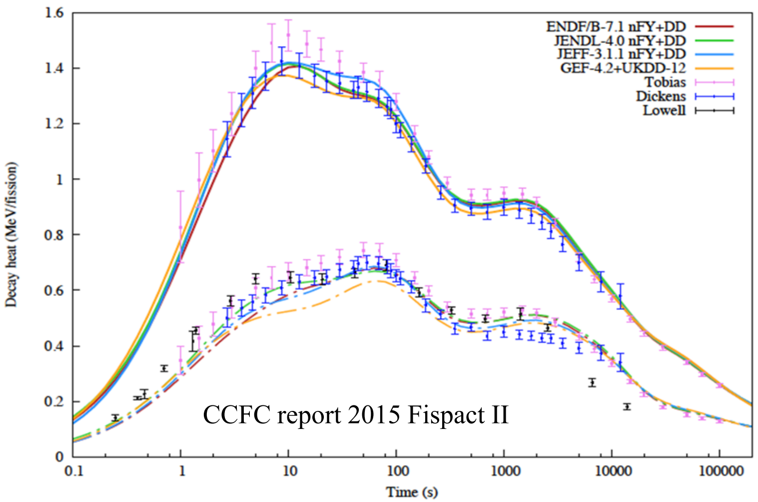
$$\mathbf{f}(t) = \sum_i \underbrace{(\bar{E}_{\beta,i} + \bar{E}_{\gamma,i})}_{\beta,\gamma \text{ decay}} \underbrace{\boldsymbol{\lambda}_i \mathbf{N}_i}_{\text{Total decay constant (half-life) and Fission Yield}}(t)$$

β,γ decay

Total decay constant (half-life) and Fission Yield

⇒ **Comparisons btw nuclear data & integral measurements show that there remains important discrepancies between data and simulations using different DataBases**

⇒ **Pandemonium effect + unknown decay schemes**

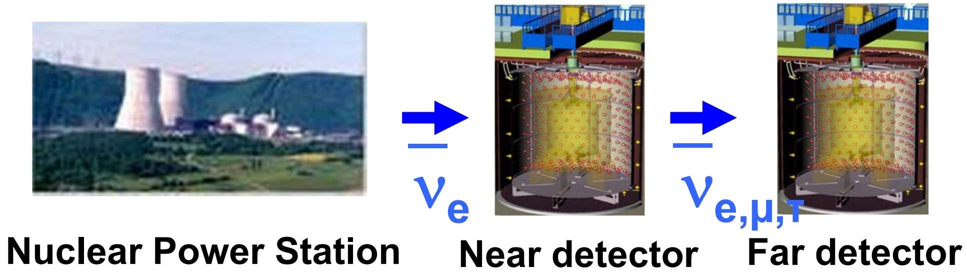


Figur **Total (solid) and gamma (dashed) decay heat from thermal pulse on ^{235}U**

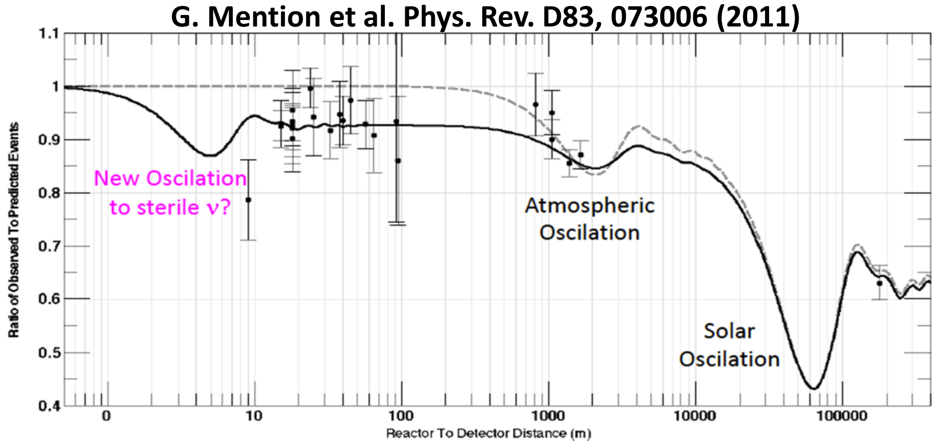
Nuclear Science NEA/WPEC-25 (2007), Report INDC(NDS)-0577 (2009), Report INDC(NDS-0551, Report INDC(NDS)-0676 (2016)

Reactor Antineutrinos

- **Measurement of the θ_{13} oscillation param by Double Chooz, Daya Bay, Reno**
  - ❑ Independent computation of the anti-ν spectra based on integral ILL measurements (Schreckenbach et al.): conversion method



- **Sterile neutrino measurement to explain the "reactor anomaly"**
  - ❑ 6% deficit of the absolute value of the measured flux compared to the best prediction ILL data
  - ❑ Bump in the full spectrum (btw 4.8-7.3 MeV)
  - ❑ Daya Bay PRL points-out a pb in the converted antineutrino spectra from ^{235}U measured beta spectrum @ILL



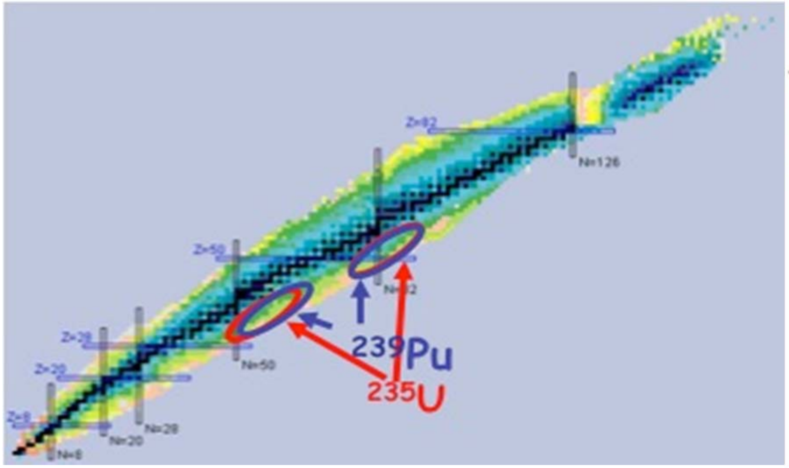
- **Next generation reactor neutrino experiments like JUNO or background for other multipurpose experiment**

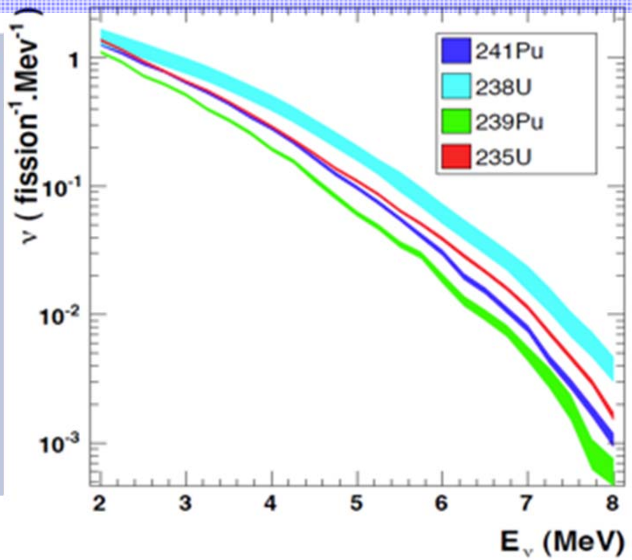
⇒ **Putting integral beta measurement of ^{235}U of Scheckenbach *et al.* and/or converted spectra and sterile neutrinos (@reactors) into question**

⇒ **Growing interest in summation method to calculate anti-ν spectra**

⇒ **Nuclear structure problematics in antineutrino spectra: Pandemonium effect, weak magnetism (see E. Liénard's talk) & first forbidden non-unique spectral shapes**

Reactor Antineutrinos





About 6 antineutrinos emitted per fission
→ About 10^{21} antineutrinos/s emitted by a 1 GW_e reactor

Use the discrepancy between antineutrino flux and energies from U and Pu isotopes to infer reactor fuel isotopic composition & power:
⇒ reactor monitoring, non-proliferation (see IAEA Report SG-EQGNRL-RP-0002 (2012).)
Idea born in the 70s, demonstrated in the 80s/90s but developed lately.

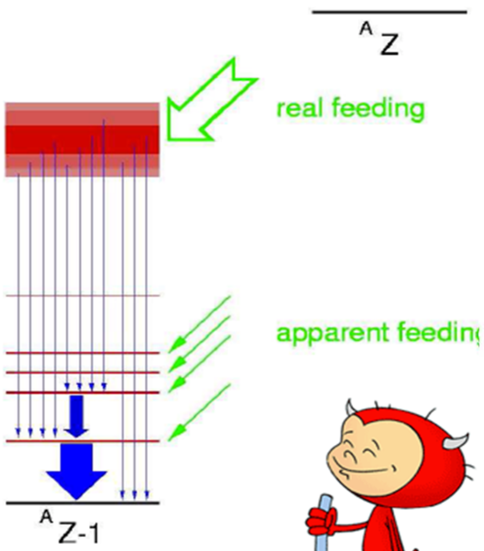
- **The International Atomic Energy Agency (IAEA): UN agency => peaceful use of atoms.**
  - ❑ **Safeguards Department is interested in: Inter alia remote and unattended tools, bulk accountancy; Safeguards by design**
  - ❑ **has shown interest in the detection of antineutrinos**
- **The IAEA Nuclear Data Section (NDS) includes the measurements for reactor antineutrino spectra in their Priority lists (CRP meetings, TAGS consultant meetings…)**

TAGS Solution to Pandemonium Effect

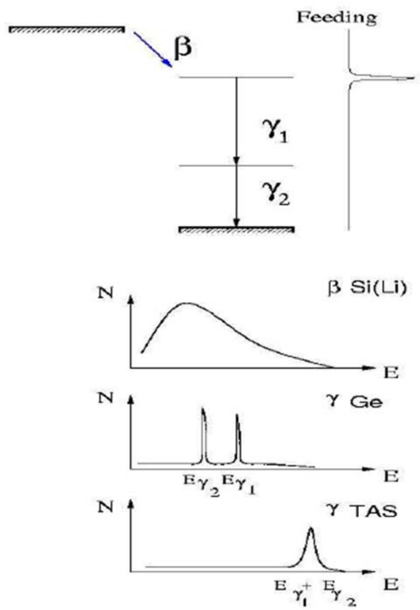
Pandemonium effect :**

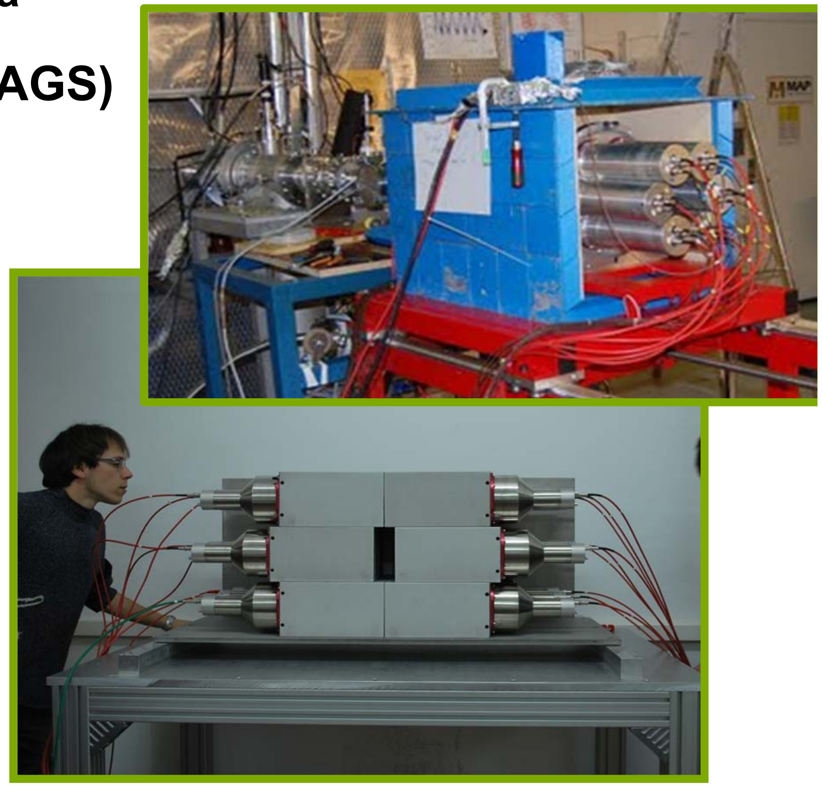
Due to the use of Ge detectors to measure the decay schemes: lower efficiency at higher energy → underestimate of □ branches towards high energy excited states: overestimate of the high energy part of the FP □ spectra

⇒ **Solution is Total Absorption γ-ray Spectroscopy (TAGS)**
Big cristal, 4π => A TAGS is a calorimeter !



Picture from A. Algora





2 TAGS arrays developed by the Valencia team (Spain, B. Rubio, J.L. Tain, A. Algora et al.): Rocinante (12 BaF2) & DTAS (18 NaI)

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

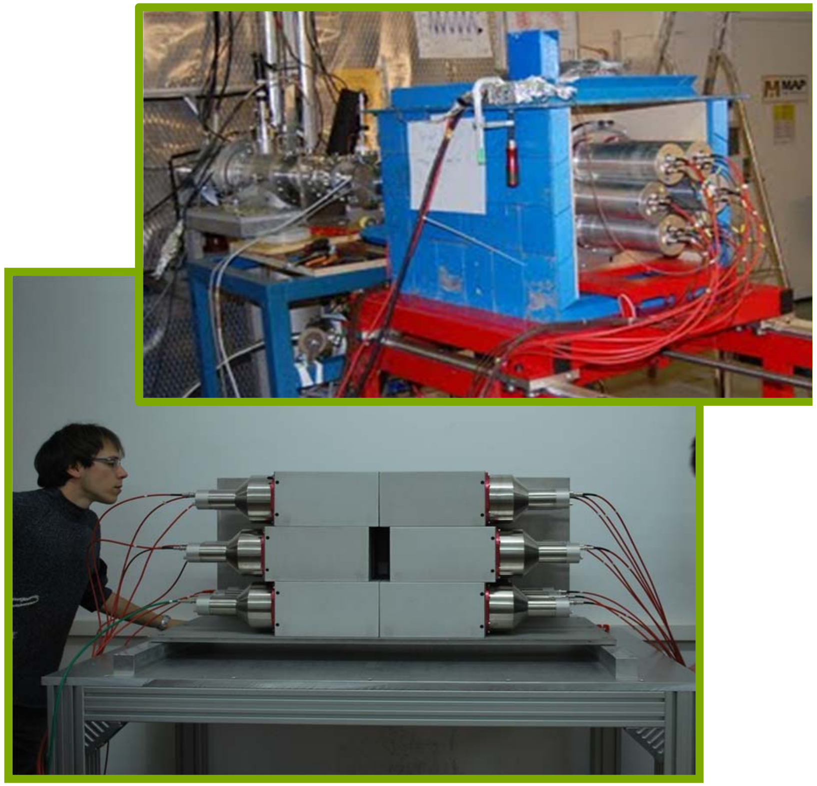
TAGS Experimental Campaigns

- **Decay Total Absorption Spectrometer (DTAS) for FAIR: used in Jyväskylä in Feb. 2014 for the reactor antineutrino proposal (physics case by Subatech):** 18 modules 15x15x25 cm3 NaI(TI) + 5" PMT
  - **12 nuclei for antineutrinos measured & 11 for decay heat**

- **BAF_2 TAGS (Surrey-Valencia): used for the 2009 measurement at IGISOL-JYFLTRAP**: ^{86}Br, ^{87}Br, ^{88}Br, ^{91}Rb, **^{92}Rb, ^{93}Rb (from Subatech proposal)**, ^{94}Rb

Collab. : Subatech, IFIC, Surrey, IPNO,IGISOL, CIEMAT, BNL, Istanbul, …

Pure beams required: Use of the double Penning trap from JYFL



2 TAGS arrays developed by the Valencia team (Spain, B. Rubio, J.L. Tain, A. Algora et al.):

V.Guadilla et al.,, Nucl. Inst. and Meth. B, in press. Online (2015) : http://www.sciencedirect.com/science/article/pii/S0168583X15012628

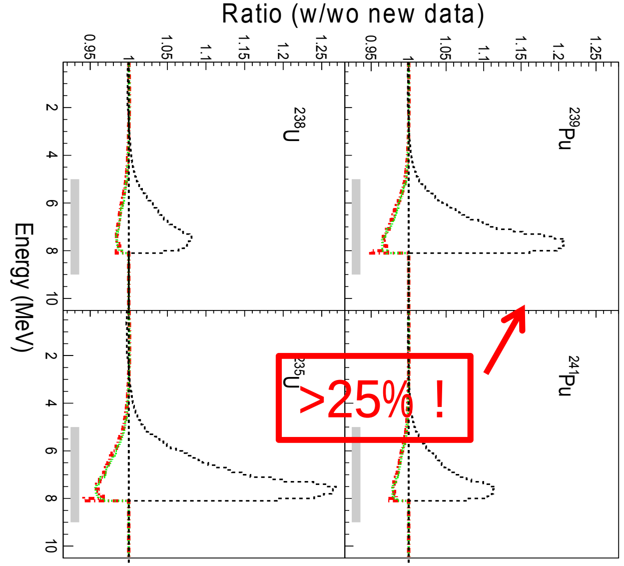
In2p3 Contribution to Reactor Antineutrino Spectrum

- Initiated by **Subatech**: **summation calculations for antineutrino spectra** (first published in **Mueller et al. PRC 2011 & Fallot et al. PRL 109, 202504 (2012)**

- First to **identify the Pandemonium effect in the summation calculations** of antineutrinos & **integrate TAGS measurements** in the calculations

- First to establish a list of nuclei requiring new TAGS measurements => **first proposal for a TAGS campaign in Jyvaskyla in 2009 in collaboration with IFIC Valencia**

- In **A. Zakari-Issoufou *et al.*, PRL 115, 102503 (2015)** β-decay properties of ^{92}Rb (**top contributor!**) + priority list of nuclei to be measured (cf. S. Grévy's presentation)



Impact of the new ^{92}Rb TAGS data on 3 modellings of the antineutrino spectra.

- **Provided an extended list of nuclei** to be measured to IAEA (IAEA-NDS report 0676 (2016))

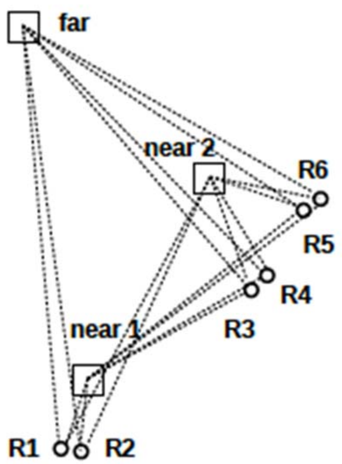
- **Data Analysis** (half-half with IFIC) + assessment of the **impact of all measurements**

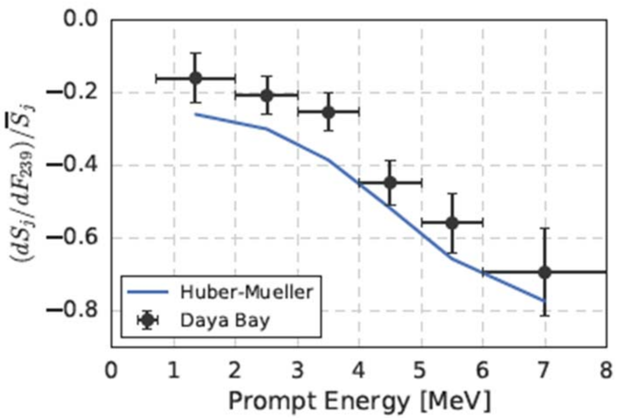
E. Valencia et al. Phys. Rev. C 95 024320 (2016) **S. Rice et al. Phys. Rev. C 96, 014320 (2017)**

⇒ **More measurements needed to improve databases and to precisely quantify the uncertainties associated to the summation calculations**
⇒ **More Results to come in 2018 with the results of the Jyvaskyla campaign in 2014 (2 PhDs)**
⇒ **New experiment to measure the shape of β spectra from non-unique forbidden transitions (E-Shape), R&D of the detector on-going @ Subatech, collab. IFIC & Surrey**
⇒ **TAGS @ ALTO**

Context by end 2017…

In 2017: Daya Bay's new result about the reactor anomaly: pb is in the ^{235}U spectrum!!!





F. P. An et al. (Daya Bay Collaboration), ``Evolution of the Reactor Antineutrino Flux and Spectrum at Daya Bay," Phys. Rev. Lett. 118 (2017).
+ Viewpoint by M. Fallot (Subatech)

⇒ Measured antineutrinos from **six 2.9-thermal-gigawatt reactor cores**, which were located either at Daya Bay or at the Ling Ao power plant in China

⇒ **Deficit in detected antineutrinos** compared to predictions **depends on the relative fractions of ^{235}U, ^{239}Pu, ^{238}U, and ^{241}Pu** in the reactor.

⇒ **^{235}U fissions produced 7.8% fewer antineutrinos than predicted**—enough of a discrepancy to explain by itself the entire antineutrino anomaly !!!

⇒ In contrast, the discrepancy = **almost zero for ^{239}Pu fissions**.

Previous hints were pointing to ^{235}U: ArXiv:1609.03910, 1608.04096, 1512.06656.

BUT https://arxiv.org/abs/1709.04294: **sterile neutrino hypothesis cannot be rejected based on global data**

Societal Impact: Nuclear Data

Nuclear Science
NEA/WPEC-25

ISBN 978-92-64-99034-0

International Evaluation Co-operation

VOLUME 25

ASSESSMENT OF FISSION PRODUCT DECAY DATA FOR DECAY HEAT CALCULATIONS

A report by the Working Party on International Evaluation Co-operation of the NEA Nuclear Science Committee

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INDC(NDS)-0676
Distr. EN, ND

INDC International Nuclear Data Committee

Total Absorption Gamma-ray Spectroscopy for Decay Heat Calculations and Other Applications

Summary Report of Consultants' Meeting

IAEA Headquarters
Vienna, Austria

15-17 December 2014

Prepared by

Paraskevi Dimitriou and Alan L. Nichols

IAEA Nuclear Data Section
Vienna, Austria

Fission Product Decay Data:

IAEA
International Atomic Energy Agency

INDC(NDS)-0683
Distr. G, ND

INDC International Nuclear Data Committee

Summary Report of

2nd Research Coordination Meeting

Development of a Reference Database for Beta-Delayed Neutron Emission

IAEA Headquarters, Vienna, Austria
23 – 27 March 2015

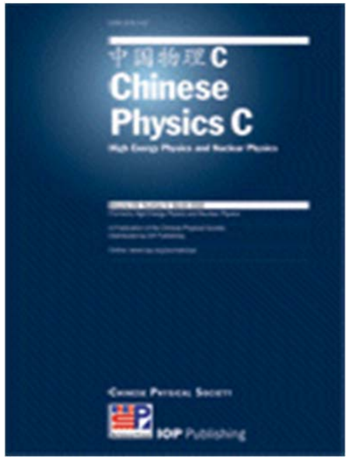
⇒ **It is important to ensure that the measured data will be made available for the "users" worldwide, this is done through the data evaluation process**

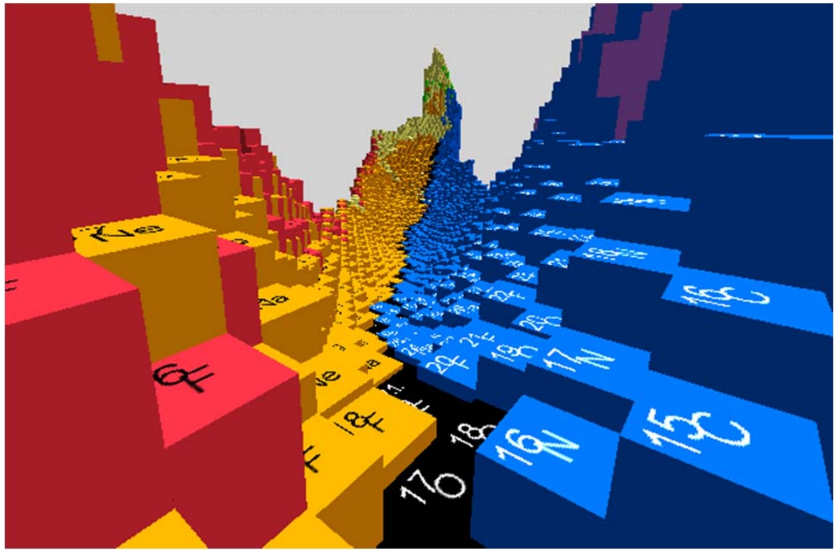
⇒ Participation (invitations) to Consultant Meetings or Coordinated Research Projects organized by the Nuclear Data Section of the IAEA, to JEFF meetings organized by the NEA, **gathering data evaluators**, **other experimentalists worldwide and theoretician**s : public reports, **list of priority measurements (list for antineutrinos provided by Subatech)**, constitution of new databases, recommandations…

Societal Impact: Nuclear Data

Atomic Mass Evaluation

Most cited publication in nuclear physics!





Published in 1983, 1993, 2003, 2012, **2016**

Next AME: 2020

Coordinator: M. Wang – IMP

Contributors:

- G. Audi – CSNSM
- F. Kondev – ANL
- S. Naimi – RIKEN
- W. Huang – CSNSM (Ph.D. 2018)

Almost 40 years of tradition at the CSNSM AME publication now coordinated by: M. Wang at IMP (Lanzhou), who was a CSNSM visitor from 2010-2012.

A Common Need for Models…

- In all three topics (astrophysics, reactors & neutrinos): a **common need for predictive reliable nuclear structure microscopic models:**
  - contribution of unknown decays still important in decay heat & antineutrino spectrum calculations, + r-process relies almost only on models…
  - importance of experimental constraints: GT strength distribution, Pn, masses, $T_{1/2}$…
  - As an example: collaboration theory (CEA) – experiment (Subatech), 1PhD on-going

- In astrophysics, **close interplay with modelization of core-collapse & nucleosynthesis processes** :
  - When thoery @ in2p3 = clearly a strength: example of Core-Collapse Project in LPC Caen (exp & theory), 2 PhDs on-going
  - Important for the identification of relevant measurements for instance

- In reactor & neutrino physics, **close interplay with modelization of antineutrino emissions, & simulations of reactor designs**
  - When done @ in2p3 = clearly a strength: identification of relevant measurements + assess the impact of the performed measurements, example in Subatech

Not mentioned here …

- Effet de l'écrantage électronique sur les durées de vie des noyaux dans les combustions hydrostatiques (P.Ujić et al., Phys. Rev. Lett. 110, 032501 (2013) et thèse en cours, GANIL, LPC Caen)

- Mesures de masse pour l'étude des étoiles à neutrons (CSNSM, ISOLTRAP) (^{82}Zn from Wolf et al. Phys. Rev. Lett. (2013) et ^{79}Cu from A. Welker et al. PRL (2017))

- Contributions de l'in2p3 pour l'évaluation de la puissance résiduelle (Subatech)

- Autres motivations reliées au cycle du combustible:
  - Influence des données de structure sur les observables de fission (O. Litaize CEA Cadarache): schémas de décroissance bêta/gamma, Pn, Sn, spin/parités,… (inputs du modèle de fission FIFRELIN)
  - Utilisation de raies gamma “connues” pour la normalisation de mesures de rendements de fission: parfois les données utilisées souffrent de l'effet Pandemonium (A. Chebboubi CEA Cadarache)

THANK YOU !