Nuclear Data at CEA

Sylvie Leray, CEA/DRF/Irfu

Consultancy Meeting on the Needs for a Comprehensive European Plan to Acquire and Curate Nuclear Data,

IAEA Vienna, 25-27 April 2023

Nuclear Data at CEA

1. **Nuclear Data at DES (Energy Division)**
   R. Jacqmin (DES/IRESNE)
2. **Nuclear Data at DRF (Fondamental research Division)**
   A. Letourneau, D. Doré, F. Gunsing, J.C. David (DRF/Irfu)
3. **Nuclear Data at DAM (Military Applications Division)**
   C. De Saint-Jean (DAM/DIF)
4. **Nuclear Data at DRT (Technological Research Division)**
   M. Kellet, X. Mougeot (DRT/LNHB)
5. **Conclusions**

1. Nuclear Data at DES

R. Jacqmin (IRESNE)

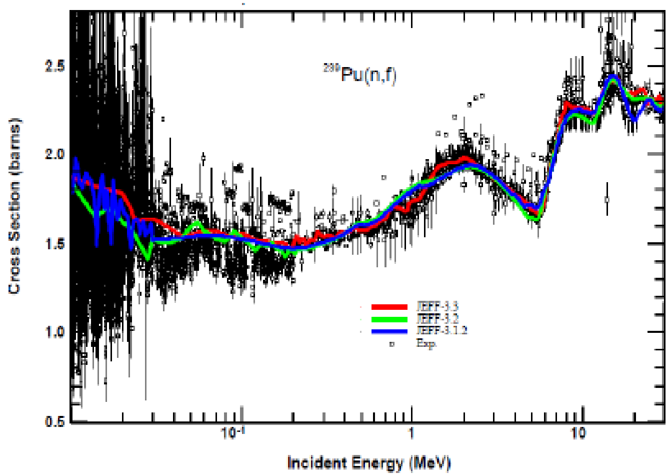
General scope of ND activities

❑ Scope

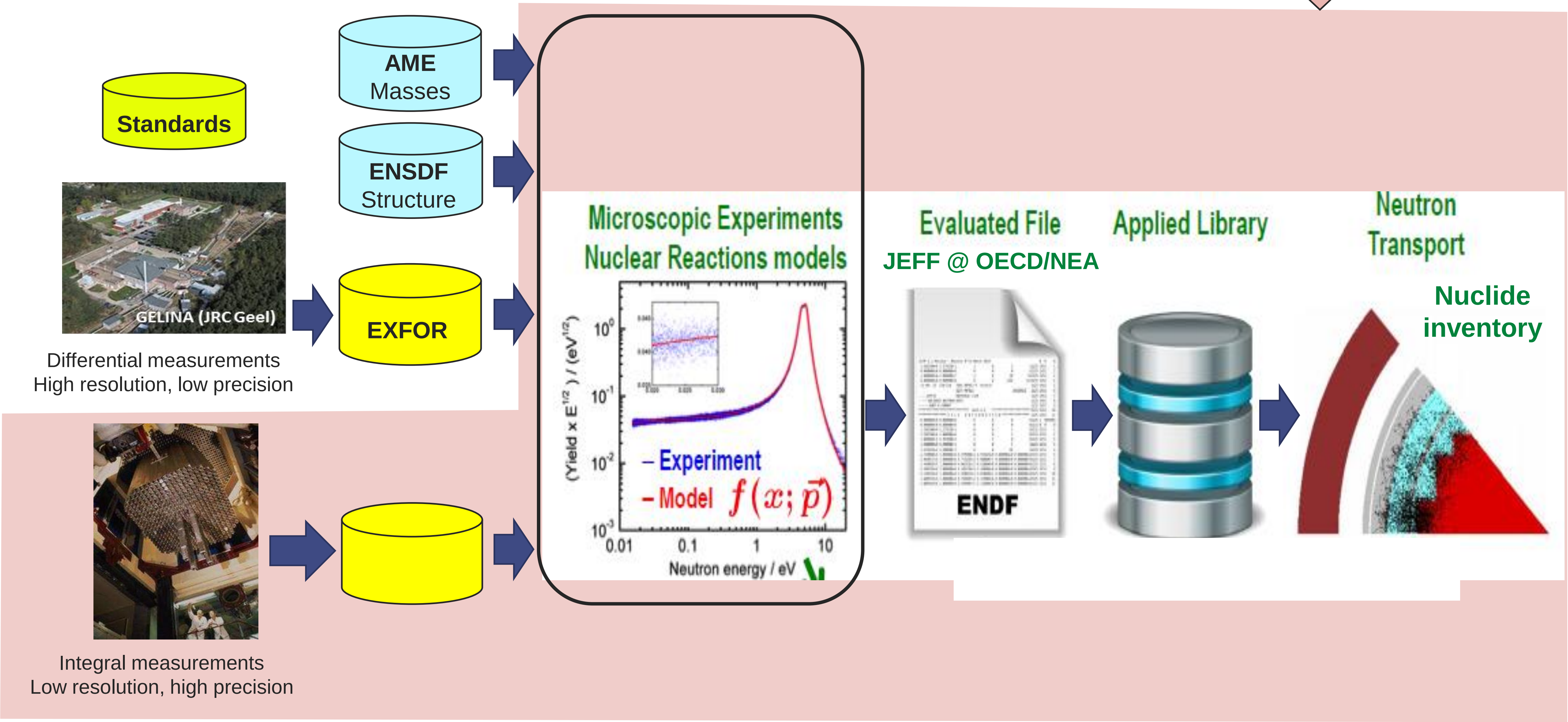
- ➢ Activities focused on nuclear data for **fission reactor applications**, including fuel cycle inventories
- ➢ French PWRs + fuels & nuclear systems of interest to France and the CEA R&D programs
- ➢ Strong connection with the CEA/DES simulation program: neutron transport and inventory code (APOLLO3, TRIPOLI4, DARWIN,…) development + validation
- ➢ Internal + external users

❑ Nuclear data of interest

- ➢ Structure data and radioactive decay data
- ➢ Reaction data: **neutron** interaction cross sections with nuclei, nature-multiplicity-energy distribution of emitted particles, fission yields, energy released,… = $f\,(E_{inc})$, **0-20 MeV**
- ➢ Corresponding uncertainties

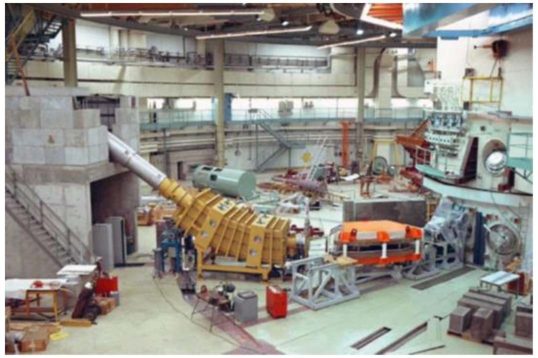


Synoptic of DES Nuclear Data Activities



Activities → ~12 Permanent Staff + PhD Students

- **Differential measurements**
  - Not done at DES ⇒ Reliance on collab. with CEA/DRF, CNRS, JRC Geel, CERN n-TOF, GANIL/NFS, ILL,…
  - Also for material procurements and sample preparation



- **Integral measurements**
  - Data from DES critical facilities and French power reactor operation
  - Since the shutdown of the DES critical facilities in 2018, reliance on international collaborations for acquiring new (validation) data + for detector developments

- **Model and code developments, evaluations**
  - 10+ years of developments integrated in CONRAD, FIFRELIN
  - Expertise in resonance energy range
  - Collaborations with CEA/DAM, CNRS/IN2P3 and others: bilateral, NEA, IAEA, EC projects,…
  - Strong involvement in JEFF

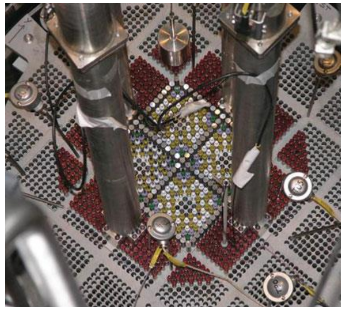
- **Validation**
  - Analyses of experiments: C/E, sensitivity/impact studies, uncertainty assessment
  - Very important, involves reactor physicists

ND Needs (1/2)

- **Evolving Nuclear Context**
  - Requirements from French ASN Guide N°28 (2021)
  - Recent decision to extend the French PWR lifetime
  - EPRs to start operating
  - SMR NUWARD
  - Many **new reactor concepts** proposed by newcomers

- **At the same time…**
  - Good performance of current ND files for existing reactors and fuel cycle
  - ND needs are **application and objective dependent**
  - ND improvement cycles remain long ⇒ Anticipation needed
  - ND uncertainties tend to dominate in reactor simulation results. Error compensations in cross section files are difficult to remove + many covariance data are still lacking ⇒ Improvements needed
  - Progress in nuclear theory and in the microscopic description of nuclei and reactions + HPC
  - New facilities (NFS@GANIL,...) and instruments (FIPPS@ILL,...), ***but*** loss of ZPRs and expertise

ND Needs (2/2)



General Needs (JEFF4)

- Continued access to experimental infrastructure + expertise ⇒ Investments in upgraded facilities (see ongoing NEA ZPR Task Force), also collaboration in modelling and evaluation
- Improve traceability, updates, testing of JEFF files ⇒ Revised approach and practices (NEA)
- Integrate the latest theoretical advances, i.e., microscopic models "from the individual constituents to the entire nucleus", to avoid fits to postulated laws, for better internal consistency (remove error compensations)
- Adopt a systematic Bayesian approach accounting for model defects
- Systematically produce and include covariance information in the files
- New validation data

Examples of Specific Needs (some of them being worked on for JEFF4)

- The "big three": U235, U238 and Pu239 fission and capture, PFNS and multiplicities…. Again!
- Also U238 structure (to improve the inelastic cross section), Pu241, Pu240 capture, some MA data
- Na23, O, Fe, U238 inelastic cross section; double differential cross sections for Na23, Fe56, U238
- Also: Important FP cross sections, fast neutron induced fission yields, delayed neutron data,…
- Major challenge, a factor of 2-3 uncertainty reduction is required in some cases!

2. Nuclear Data at DRF

A. Letourneau, D. Doré, F. Gunsing, J.C. David (Irfu)

Nuclear Data at Irfu/DPhN

LEARN - Study and Applications of Nuclear Reactions: ~9 permanent staff, several PhD-postdoc

- Nuclear data measurements
  - Neutron capture and fission cross sections measurements on actinides:
    - 1998-2010 : measurements with thermal neutrons at ILL for almost all minor actinides
    - Since 2000 : measurements in the resonance region at n_TOF
  - Fission yields and fragments properties measurements:
    - Since 2010 : measurements of the yields at ILL with the Lohengrin spectrometer and the gamma-prompts with the FIPPS spectrometer
    - Starting 2022 : measurements of the yields at NFS with the Falstaff spectrometer
  - Decay of fission products:
    - Since 2004 : measurements of fission antineutrino energy spectra (Double-Chooz, Nucifer, Stereo and Nucleus)
- Integration of nuclear data knowledge in codes
  - Since 2000: INCL code developments for energetic nucleons induced reactions
  - Since 2007 : modeling of fission electron and antineutrino energy spectra
- DPhN is also producing knowledge on
  - Nuclear structure and reactions with different experiments at GANIL, GSI, RIKEN, Isolde
  - Microscopic calculations of nuclear structure with different techiques (ab-initio approach, mean field, ..)

Study of neutron-induced reactions - present

- Measurements at neutron time-of-flight facilities
  - n_TOF at CERN
  - GELINA at JRC-Geel;
- Scientific and technical responsibilities
  - Neutron capture measurements, including in the presence of fission
  - Study of the photon strength functions and level densities in the gamma decay following neutron capture on the isotopes ^{234}U, ^{236}U and ^{238}U
  - Data analysis and production of EXFOR data
  - Development of neutron flux monitors
  - MC simulations of detector response

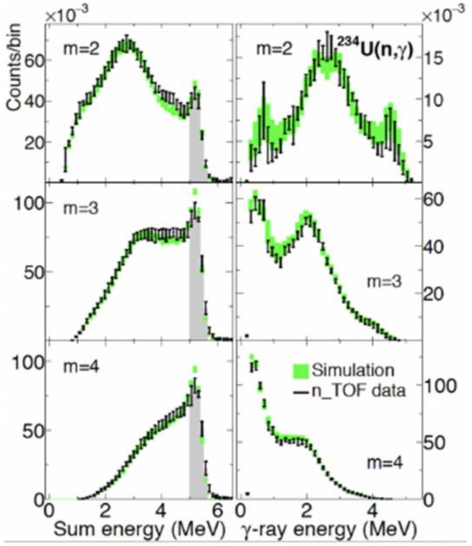
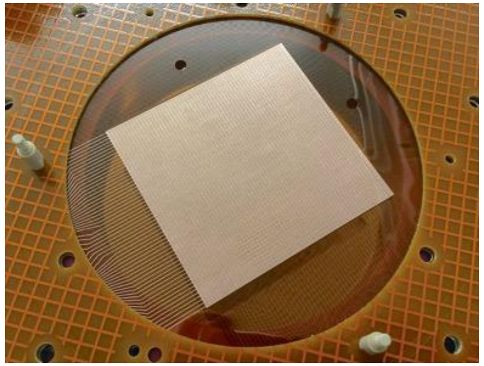


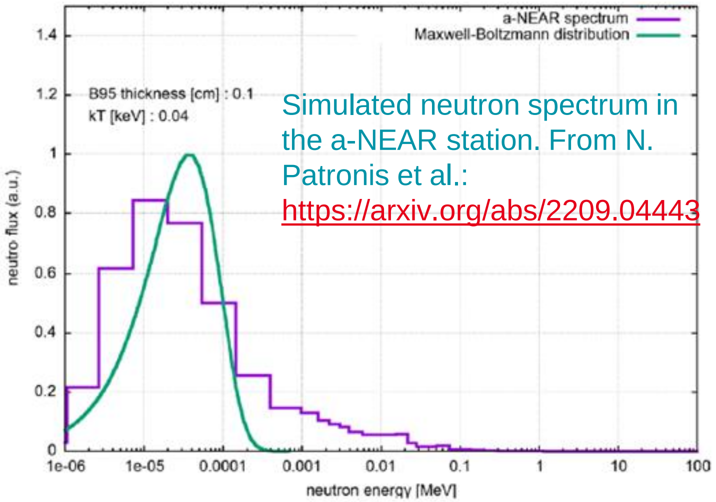
Figure 4: Comparison of simulated and measured data for gamma rays emitted by 235U after the 234U(n,?) capture reaction.

.From J. Moreno-Soto et al.: https://doi.org/10.1103/PhysRevC.105.024618



Study of neutron-induced reactions - future

- Measurements
  - Measurement of ^{241}Pu capture and fission yields at n_TOF and fission cross section at GELINA
  - Possible experiments for astrophysics at the new NEAR station providing quasi-maxwellian flux



Simulated neutron spectrum in the a-NEAR station. From N. Patronis et al.: https://arxiv.org/abs/2209.04443

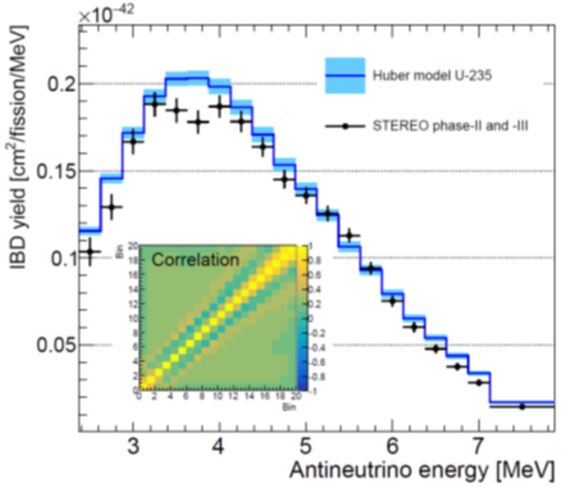
- Technical developments
  - ANR Micromegas-XY: a "transparent" neutron detector with unprecedented position and time resolving data acquisition capabilities, for use at GELINA, n_TOF, nELBE or NFS for neutron flux measurements, fission and (n,α) cross section measurements, and neutron beam imaging

Difficulty: availability of targets particularly, but not only, for radioactive isotopes

Studies on beta-decay - present

- Measurements of reactor antineutrinos
  - Double Chooz @ Chooz reactors
  - Nucifer @ OSIRIS reactor
  - Stereo @ ILL reactor
- Scientific and technical responsabilities
  - Fission anti-neutrinos modeling emitted by a nuclear reactor (Huber-Mueller model)
  - Data analysis and MC simulations of the Double Chooz and Nucifer detectors
  - Development of the Stereo experiment (spokesperson, MC simulation of the detector and data analysis)
- Main results
  - Very precise anti-neutrinos energy spectra for ^{235}U and ^{239}Pu
  - Comparison with the Huber-Mueller model shows discrepancies which are not due to the existence of non-standard particle (i.e. sterile neutrino)

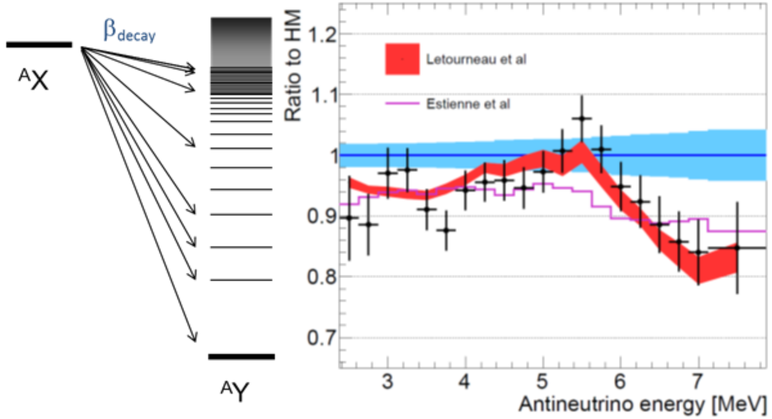
.From A. Letourneau et al.: https://doi.org/10.1038/s41586-022-05568-2



Studies on beta-decay - future

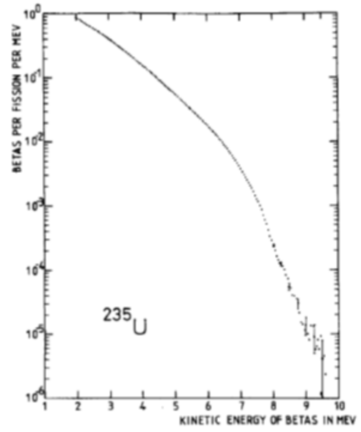
- Modeling
  - Full description of the β^--decay within the summation approach (sum over more than 800 fission fragments and more than 10000 transitions for neutron rich isotopes)
  - Development of a beta-decay strength model for fission fragments to complete the ENSDF database and to correct data from the Pandemonium effect or missing data
- Measurements
  - Delayed gamma emitted after fission with the FIPPS spectrometer
  - Fission electron spectra for ^{235}U and ^{239}Pu with dedicated electron spectrometer to be defined
- Challenges for beta-decay:
  - Decay data suffers from missing data and Pandemonium effect in particular for neutron rich isotopes
  - Electron energy spectra are old measurements from the 80's-90's and difficult to redo (need for precise spectrometer insensitive to gamma-rays and installations)
  - No evaluation effort in Europe on decay data (only ENSDF from NNDC exist)

Comparison of Stereo with beta-strength model



.From A. Letourneau et al.:
https://doi.org/10.1103/PhysRevLett.130.021801

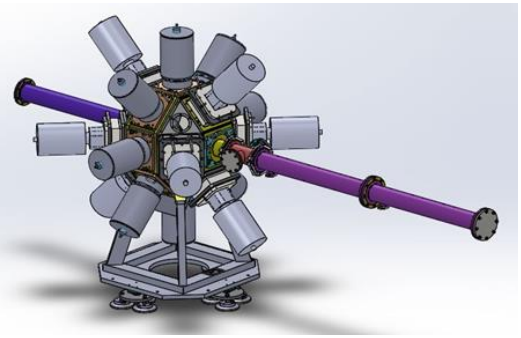
Fission electron spectrum for ^{235}U measured in the 80's

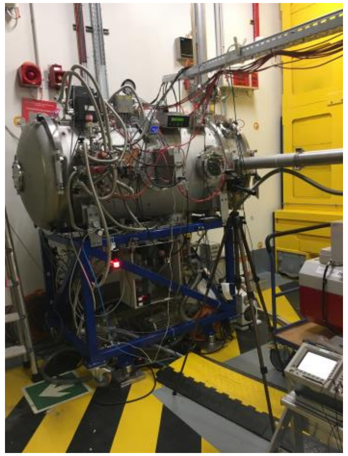


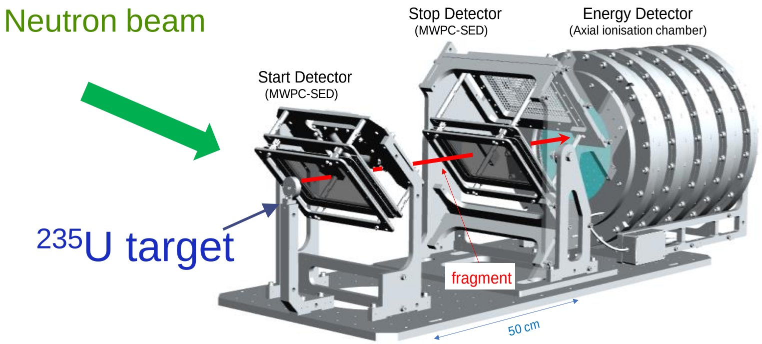
Studies on nuclear fission - present

- Measurements at ILL
  - Independent Fission yields of ^{241}Am at Lohengrin
  - Gamma rays analysis for fission product for the EXILL campaign and FIPPS spectrometers for neutron induced fission on ^{235}U
  - MC simulations of the FIPPS HPGe detectors
- Measurements at NFS (SPIRAL2-Ganil) in collaboration with GANIL
  - White neutron spectrum from 500 keV up to 40 MeV
  - ^{235}U neutron induced fission studies in 2022 with the first arm of FALSTAFF
  - Fission fragment characteristics measurement: velocity, energy, mass and, if possible, charge of the fragments
  - Correlation between variables and study as a function of the excitation energy
  - Data analysis, comparisons with existing simulations code

FIPPS spectrometer and the neutron guide





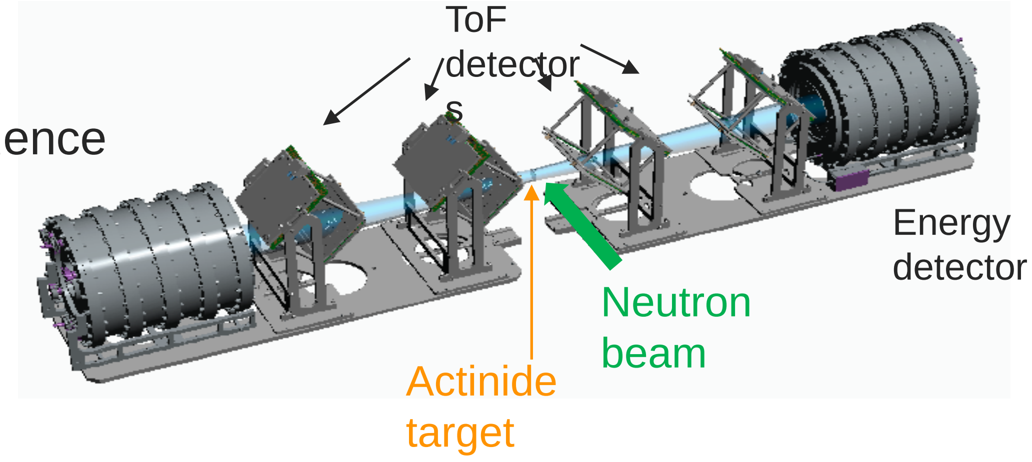


FALSTAFF spectrometer at NFS

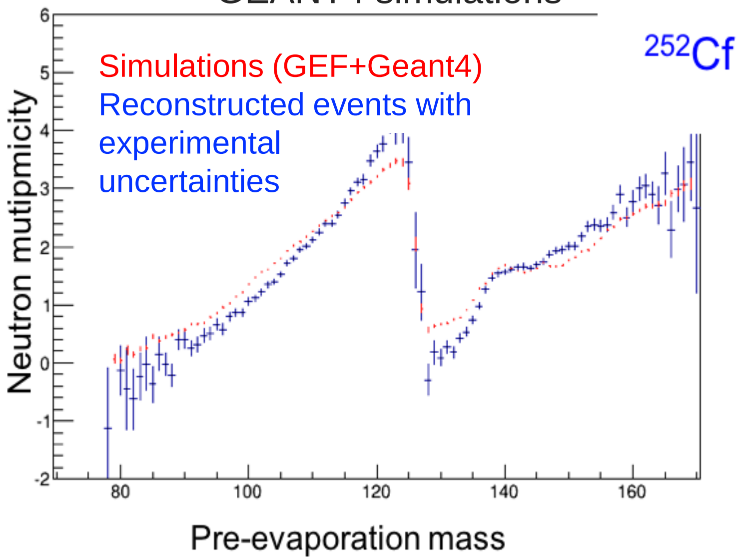
Studies on nuclear fission - future

- Measurements with FALSTAFF
  - Measurement of both actinide fission fragments in coincidence
    - Construction of the second arm
    - Pre-Evaporation fission fragment mass accessible
    - 1st Experiment expected in 2025
    - Actinides to be studied according to available targets
- Technical developments
  - Gamma detectors to be added close to the target to go toward a complete energy balance

Difficulty: availability of targets



GEANT4 simulations



Modeling of high-energy nuclear reactions

Present

Development of the intranuclear cascade model INCL coupled to de-excitation code ABLA, integrated into high-energy transport codes, GEANT4, PHITS and MCNP6

- Extension to strangeness production, neutrino, and antiproton induced reactions
- Investigation of an approach based on Bayesian statistics to estimate errors and uncertainties
  - Schnabel (2018): Estimating model bias over the complete nuclide chart with sparse Gaussian processes at the example of INCL/ABLA and double-differential neutron spectra https://doi.org/10.1051/epjn/2018013
  - Hirtz et al. (in progress - SANDA): Building a framework to optimize parameters

Future

Quantification of uncertainties and errors of the INCL/Abla models and improvement thanks to a parallel optimization of some parameters. The information needed to determine the uncertainties and errors of the results and parameters is provided by Bayesian statistics where experimental data play the role of likelihood.

Need for Numerical Data dissemination

Nuclear physicists publish their results (experimental and theoretical) but most of the time, data are not availables on a numerical support

→ Need for a numerical support for published results, to facilitate the evaluators' subsequent work

Examples of disseminations at DPhN:

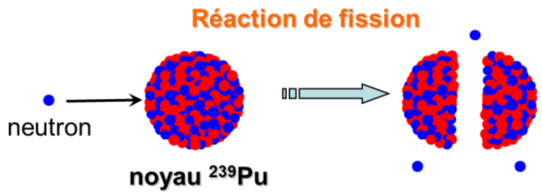
- A huge effort to disseminate n_TOF data in the EXFOR database
- Neutrino experiments as STEREO make their published results and simulations numerically available on open data storage as ZENODO@CERN
- INCL++ is in Geant4

3. Nuclear Data at DAM

C. de Saint Jean (DIF)

Nuclear Data at CEA DAM : principles

Nuclear processes simulation and understanding

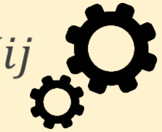


Study of the static (mass, density, energies) and dynamic properties of nuclei (nuclear structure) and associated nuclear reactions

Expertise on physical phenomena (isomers, photo-nuclear reactions, fission, reactions)

Advances in knowledge

$$\sigma_{ij} = D \frac{\pi}{k^2} \frac{T_i T_j}{\sum_k T_k} W_{ij}$$



Theory

Experiment

Nuclear Data Evaluation

- ⊗ Theoretical/experimental choices and propose a **synthesis**
- ⊗ Provide "**numbers**" for simulation codes

Precision

Completeness

Cross sections
(fission, capture, n2n,…)
Spectra and multiplicities
(neutrons, gammas…)
…

~12 Permanent Staff + PhDs + Pos-docs

Nuclear Data at CEA DAM : Experiments

Detector conception (principles/electronics) in collaboration with CNRS/CEA-DRF
Two majors points : metrology (**uncertainty reduction**) and/or innovation (multi-observables)
Goals : nuclear data evaluation, theoretical contraints and new physics

Getting rid of Compensation effects

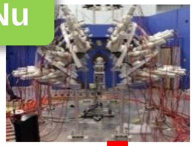
Nuclear Reactions

Fission

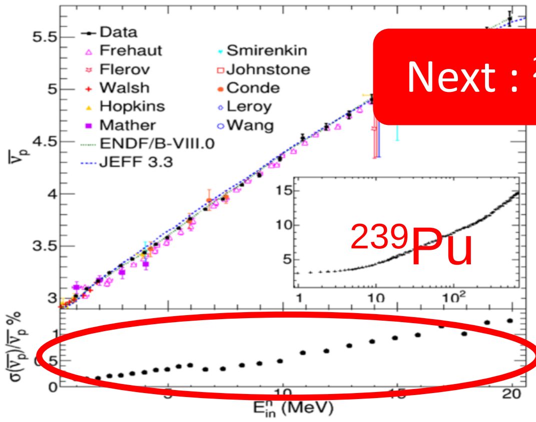
Actinides

DAM/NNSA collaboration
$\overline{\nu}$ and χ measurements
^{239}Pu(2017), ^{235}U(2019) and ^{238}U(2022)

Chi-Nu



Vendeta



Next : ^{240}Pu and σ_f

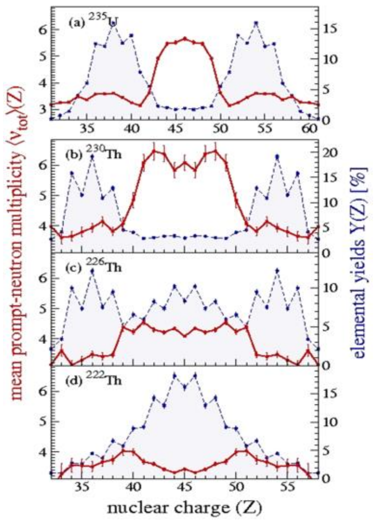
Experimental uncertainty reduction for $\overline{\nu}$

DAM/GSI collaboration : SOFIA
***Fissions Yields* measurements ; U,Th…**

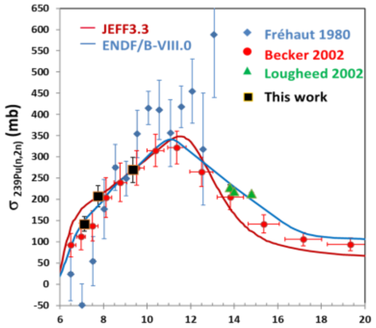
SOFIA : new compact symetric fission mode observed

May be related to tensor term in nuclear effective interaction

Next : ^{239}Pu at GANIL/VAMOS



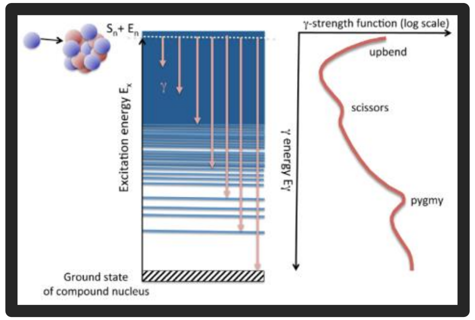
^{239}Pu (n2n) measurement at CEA-DIF with NENUPHAR tandem



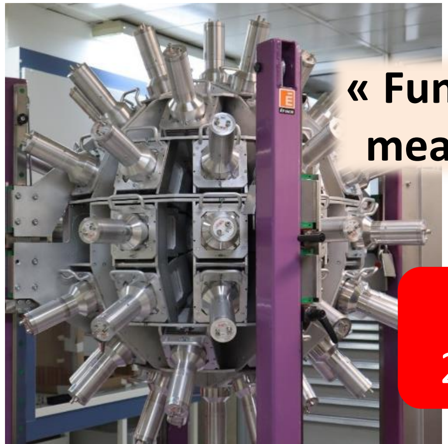
Next : ^{239}Pu (n2n) at GANIL/NFS ([9MeV-20MeV])

New Paradigm

Strength function and level density measurements with SFYNCS device at CEA-DIF



A.C. Larsen et al., Prog. Part. Nucl. Phys. **107** (2019) 69.



« Fundamental » measurements

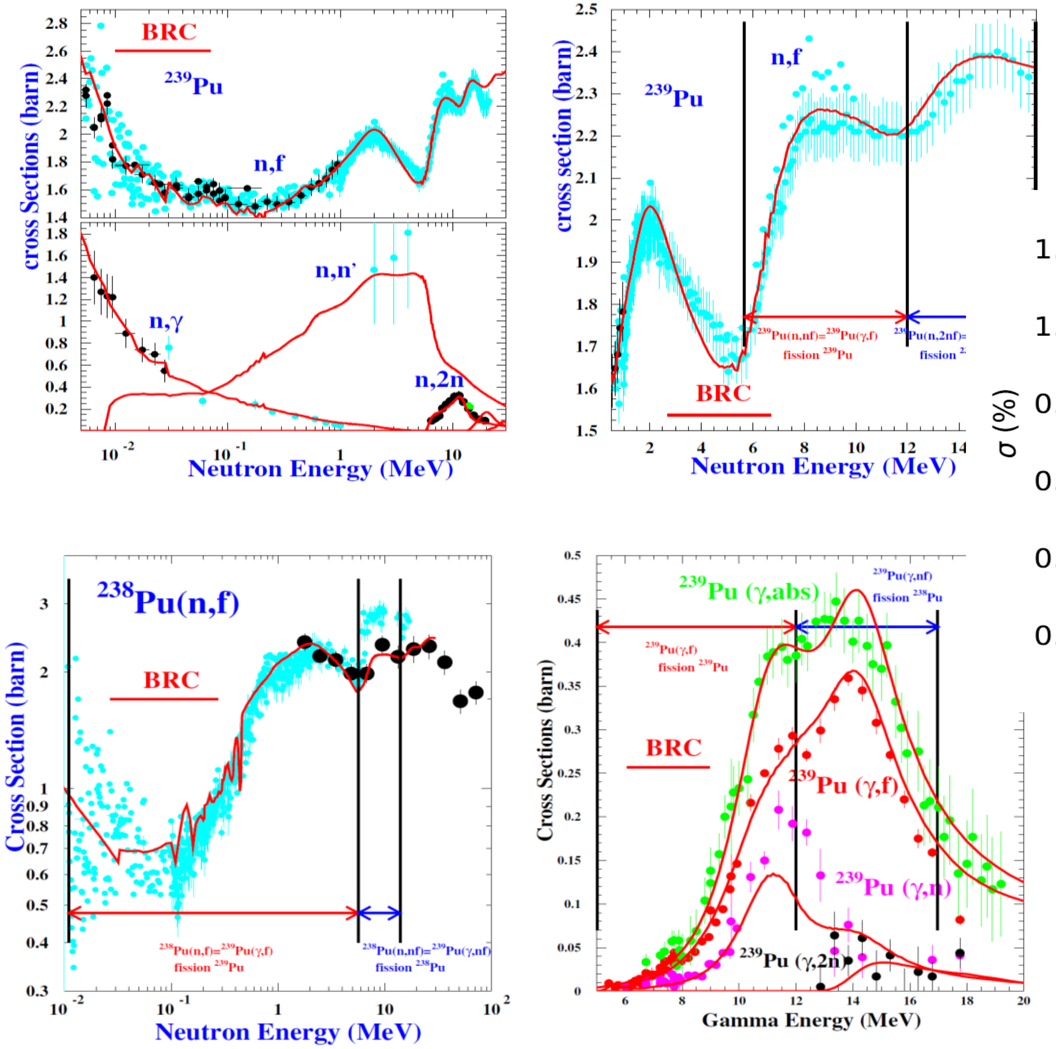
Next : 2023-2025

cea

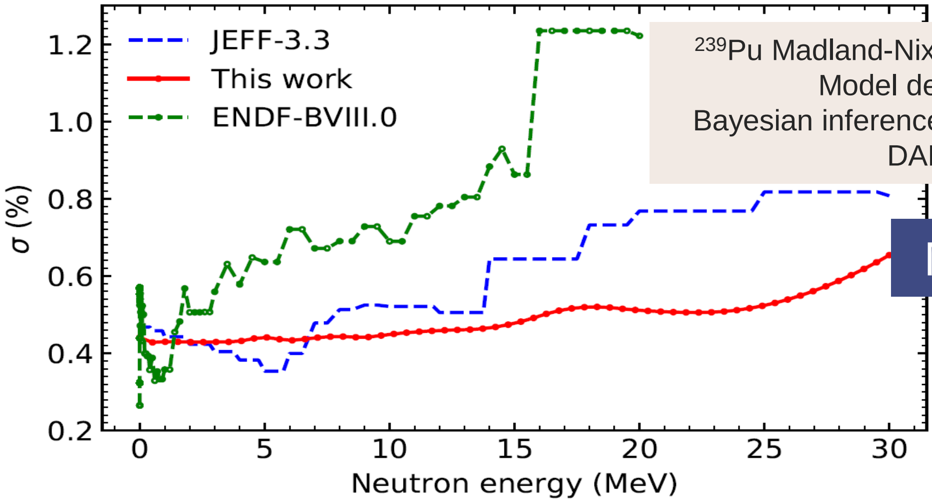
Nuclear Data at CEA DAM : Theory/Evaluation

Evaluation | Nuclear Reactions | Uncertainties and AI | Fission

^{239}Pu new evaluation underway (n and γ)
Same fission parameters to describe n+^{239}Pu, n+^{238}Pu, γ+ ^{239}Pu

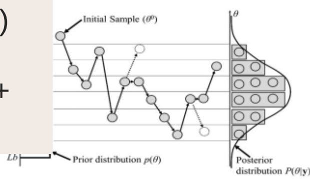


New
^{239}Pu $\bar{\upsilon}$ and χ measurements
→new evaluation with reduced uncertainties

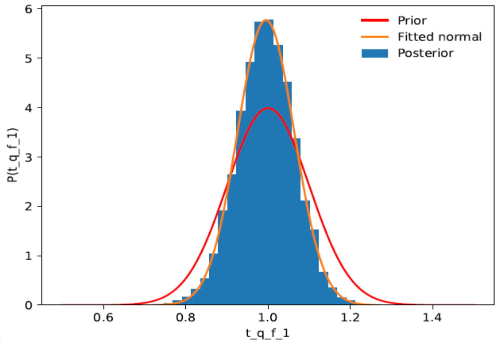


^{239}Pu Madland-Nix model (~20 parameters)
Model defect treatement
Bayesian inference with usual experiment + DAMM/NNSA

@Lee, Jaewook et al. (2015



Markov Chain Monte Carlo



Standard deviation on ^{239}Pu $\bar{\upsilon}$
Work in progress

More and more microscopic component in evaluation (QRPA)
Towards « reference » calculations for uncertainties (MCMC)
Impact of recent measurements to disentangle compensation effects
The road to JEFF4

4. Nuclear Data at DRT

M. Kellet, X. Mougeot (LNHB)

Context

Need for European autonomy on nuclear decay data by creating a strong collaborative network at a European scale

→ Existing network/working groups with expertise and tools:

- **→ Decay Data Evaluation Project (DDEP)**
- **→ International Committee on Radionuclide Metrology (ICRM) Beta spectra & Nuclear Decay Data WGs**
- **→ JEFF Decay Data WG**

→ Coordination by CEA LNHB – could be a starting point?

Challenges

- Ensuring sufficient funding and manpower
- Decreasing the timescale of the nuclear data pipeline: not more than 2 – 3 years from publication to evaluation
- Identifying the nuclei that are critical for the different application communities: radiotherapy, new reactors, proliferation and monitoring issues, etc.
- Recommending the most pertinent measurements to improve nuclear data for each nucleus
- Answering users' needs: inclusion of TAGS data, provision of covariance matrices in decay data, new systems, etc.
- Modernizing the database and the evaluation and dissemination tools

Resolution 2 of the 27th CGPM on the Global digital Transformation and the International System of units: development of an SI Digital Framework and implementation of a digital traceability chain

Evaluated nuclear decay data - worldwide

Nuclear decay data is pivotal in many topics of fundamental research, but also for a large number of applications: nuclear engineering, radiation shielding, nuclear reactors, nuclear waste, radionuclide metrology, radioprotection, radiotherapy, dosimetry etc.

→ **The beginning of such evaluated data goes back to Marie Curie!**

ENSDF database from the International Network of Nuclear Structure and Decay Data Evaluators (NSDD).

✓ Network coordinated by the IAEA

✓ Comprehensive: aims at providing data for any existing nucleus

BUT

- Management, dissemination, review process, guidelines and rules → **Controlled in main part by USA**
- Evaluation of nuclear decay data → **Major funding within the USA, very limited elsewhere**
- **Europe contribution to ENSDF is extremely poor** (~0.5 FTE from Bulgaria, Hungary and Romania)
- Evaluation work is undertaken by mass chain, limited interest for many physicists and communities
- From the publication of a new measurement to its appearance in an evaluated database, timescale is very long (~10 – 15 years, sometimes more)

Evaluated nuclear decay data – Europe

The Decay Data Evaluation Project (DDEP)

International collaboration initiated in 1993 by CEA LNHB (France) and PTB (Germany), joined by a few evaluators from China, the UK, the USA, Romania, Russia and Spain from 1994 to 2016.

The goal is not to compete with ENSDF evaluators but to provide data to a different community with different needs.

Evaluation work performed for individual nuclei, including a detailed report of the evaluation procedure. Current DDEP database contains **~230** evaluated decaying nuclei.

- ✓ **Collaboration coordinated by CEA LNHB**: database, dissemination, evaluations and review process
- ✓ Atomic and nuclear decay data provided to the metrology community and to non-specialists
- ✓ Data officially recommended and published by the International Bureau of Weights and Measures (**BIPM**)
- ✓ CEA LNHB is responsible for the decay data sub-library in the Joint Evaluated Fission and Fusion library (**JEFF**), which is the reference European nuclear data library
- ‼ Strong decrease of manpower since 2016 due to retirements, international context and funding agencies
- ‼ Current effort (~1 FTE) essentially comes from CEA LNHB (France) – currently supported through the French metrology programme. This expertise in nuclear decay data is unique in Europe

Example of what not to do – AME

The Atomic Mass Evaluation provides Q-values which are of the utmost importance in any topic of nuclear physics as they define the available energy in any nuclear reaction or radioactive decay.

The reference database is **AME (Atomic Mass Evaluation)**, regularly updated and published.

- ✓ Pioneering work from A.H. Wapstra (The Netherlands) in 1960.
- ✓ Joined by G. Audi (France) in 1983.

AME 2003 is the last version from Europe.

‼ Despite the appearance of an international collaboration, **the evaluation activity was transferred from France to China** when G. Audi retired from CNRS (around Fukushima accident).

The next versions (2012, 2016, 2020) were all published in Chinese Physics C.

→ **Since then, China entirely controls one of the most important parameters in nuclear physics.**

→ **It is a complete loss of sovereignty for France and for Europe, while low-carbon electricity becomes critical.**

5. Conclusions

Nuclear data at CEA

- The CEA, with all its divisions involved, constitutes a significant, and probably unique in Europe (and in the world), high expertise work force, spanning the whole chain of ND production, from differential measurements and theory to validation and evaluation
- All the work is done in close collaborations with national (in particular CNRS) and international organisations
- CEA benefits from its close relationships with industrial stakeholders (EDF, FRAMATOME, ORANO)
- CEA actively participates to many committes/bodies related to ND: INDC, JEFF, NEA, IAEA CRPs, ND conferences, etc…

Considerations for the future

- Needs for the future, mostly driven by the recent « revival of nuclear power »
  - Extension of current reactors lifetime
  - SMRs
  - New reactor concepts proposed by newcomers
  - Fusion (compact HTS systems)
  - But also radiation protection, radiotherapy, dosimetry, proliferation, monitoring
- A continuous international effort is needed to master the whole chain from the differential measurements to the inclusion of an evaluation into a library:
  - Ensuring sufficient funding and highly specialized dedicated manpower
  - Access to experimental infrastructure and investments in upgraded facilities (see ongoing NEA ZPR Task Force)
  - Collaboration in theory, modelling and evaluation
  - Decreasing the timescale of the nuclear data pipeline, in particular from publication to evaluation
  - Identifying the nuclei that are critical for the different application communities
  - Recommending the most pertinent measurements to improve nuclear data for each nucleus

Thank you

CEA SACLAY
91191 Gif-sur-Yvette Cedex
France
Sylvie,leray@cea.fr
Standard. + 33 1 69 08 14 90