DE LA RECHERCHE À L'INDUSTRIE

EXCALIBUR
An Integral Experiment for ^{238}U(n,n') Validation at CALIBAN

DEN/DER/SPRC/Laboratoire d'Etudes de Physique | **Pierre Leconte**, David Bernard

Joint JEFF/CHANDA Meeting, Paris, April 29th, 2015

OUTLINE

- Context
- Design of the Experiment
- EXCALIBUR program
- Conclusions and prospects

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CONTEXT
Impact of ^{238}U(n,n’) on reactor calculations

- **A benchmark study of a full PWR core calculation (NEA expert group on Uncertainty Analysis in Modeling) has shown the influence of the ^{238}U inelastic scattering on several parameters**
  - Radial power tilt is impacted by ~5% using the covariance from ENDF/B-VII.0 (mean standard deviation on ^{238}U(n,n’): 10-20%)
  - Reactivity worth of control rods are impacted by ~10%

    ➔It was concluded than an uncertainty of ±5% (1σ) on U238(n,n’) was required to reach the target uncertainties on GEN-III+ and GEN-IV core calculations

- **Ongoing work at CEA on different reactor types**
  - Fast Reactors:

    - Doppler coefficient and power peak

    - Sodium Void Effect
  - Thermal Reactors: increase of the uncertainty on the power map with the size of the core: from 5% (900MWe) to 10% (1450MWe)

    -> *A. Santamarina, P. Blaise, N. Dos Santos et al., “ Nuclear Data Uncertainty Propagation on Power Maps in Large LWR Cores”, Proceedings of the PHYSOR2014 Conference, Kyoto, Japan, Sept 2014.*

- **Impact on kinetic parameters**
  - Popsy and SNEAK-7B benchs: 2-3% uncertainty on β_{eff} due to ^{238}U inelastic cross section

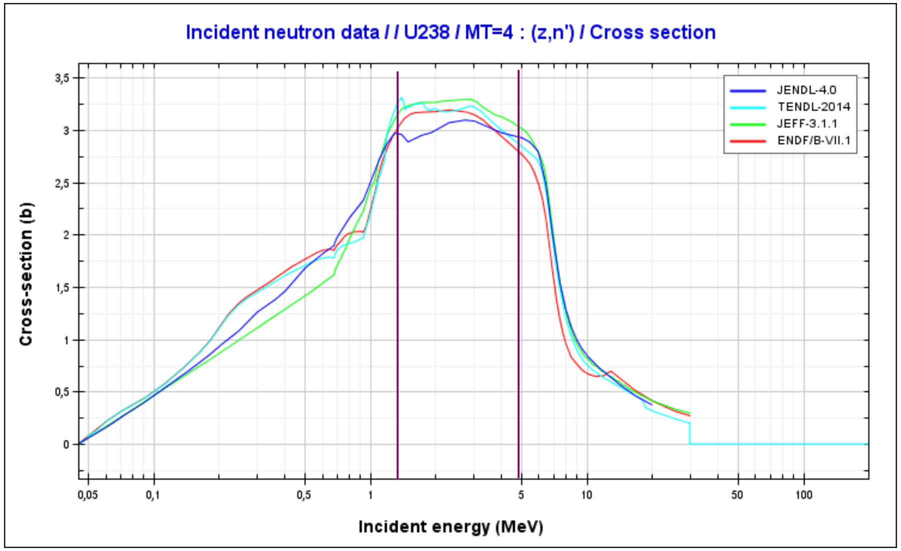
    -> *I.A. Kodeli, “*Sensitivity and uncertainty in the effective delayed neutron fraction (β_{eff})*”, NIM, A715,70-78, 2013.*

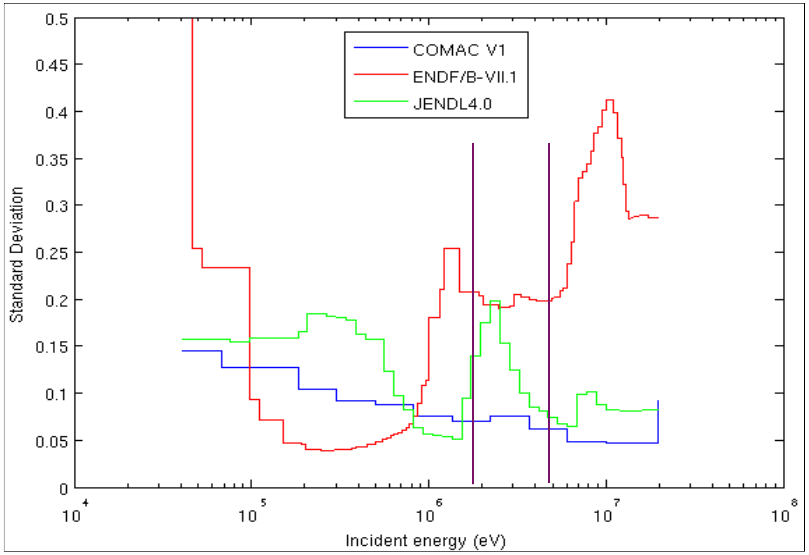
CONTEXT

^{238}U(n,n’) evaluation, covariance and benchmarking

Evaluations and covariances

- Differences on the mean plateau value: ~8%
- Uncertainty on the 2-5 MeV range: 6 to 20% (1σ)





Consistent trends from several independant integral experiments

- ^{235}U and ^{239}Pu metallic spheres, reflected or un-reflected by metallic ^{nat}U
- Spectral indices and K_{inf} = 1 experiments in in fast reactor lattices
- Radial map of large PWR core (French N4 Chooz-B1)

➔All these experiments are more sensitive to ^{238}U(n,n’) than any other ND

➔Consistent conclusion: overestimation of **11 ± 3% of JEFF3.1.1** in the [2-5 MeV] range

> *A. Santamarina, D. Bernard, P. Leconte, J.F. Vidal, “*Improvement of ^{238}U Inelastic Scattering Cross Section for an Accurate Calculation of Large Commercial Reactors*”, NDS,* 04/2014, 118:118–121.

CONTEXT
Experimental data related to ^{238}U(n,n’)

- **A lack of precise differential data:**
  - Very few data from EXFOR at no better than ±20%
  - New measurements are ongoing at GELINA (IRMM) by CNRS

  ➔Improvements are expected within the CHANDA project (WP8)

- **Shielding experiments (Na, Fe, ^{1}H…) are relevant to validate elastic/inelastic cross sections**

  ➔No similar experiments exist for ^{238}U

- **Some fast spectrum experiments (MASURCA, ZPR, ZPPR…) use a depleted Uranium reflector but with unsufficient uncertainty and/or sensitivity to ^{238}U**

- **Need to perform a dedicated integral experiment to validate ^{238}U(n,n’) with the following goals**
  - Target uncertainty of less than 3% (1σ)
  - Feedback on a wider energy range: 0.5 – 8 MeV
  - Minimize the influence of other isotopes / reactions

➔ Starting point: building a transmission experiment through a ^{238}U device with an external source and several dosimeters with various energy responses

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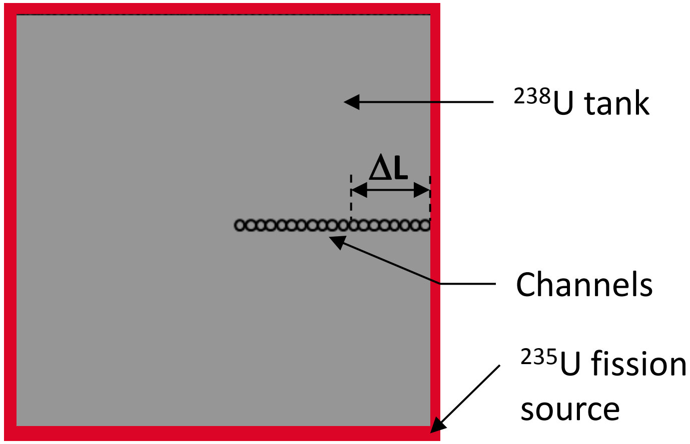
DESIGN OF THE EXPERIMENT
Benchmark specifications

- **Geometrical model**
  - ^{238}U metallic tank 40x40cm
  - 20 fictive channels, spaced by 1 cm (for activation dosimeters and FC)
  - External source: ^{235}U fission spectrum



- **4 ENDF input files of ^{238}U were processed based on:**
  - JEFF3.1.1 (official) file
  - JEFF3.1.1 file + 10% on ^{238}U inelastic scattering (full energy range)
  - JEFF3.1.1 file + 10% on ^{238}U elastic scattering (full energy range)
  - JEFF3.1.1 file + 10% on ^{238}U fission (full energy range)

- **TRIPOLI-4 calculations of different reaction rates as a function of penetration length ΔL:**
  - Thermal/epithermal responses : ^{235}U(n,f), ^{239}Pu(n,f), ^{197}Au(n,γ), ^{115}In(n,γ), ^{55}Mn(n,γ)
  - Fast responses: ^{238}U(n,f), ^{237}Np(n,f), Rh(n,n’), ^{115}In(n,n’), ^{27}Al(n,α), ^{56}Fe(n,p)

- **Reaction rate ratio R(ΔL) / R(0) as a function of ΔL was compared between JEFF-3.1.1 (reference) and the 3 modified files**

DESIGN OF THE EXPERIMENT
Comparison with JEFF-3.1.1 reference: +10% on ^{238}U(n,n') inelastic xs

Penetration length (cm)	Au197(n,γ)	In115(n,γ)	Mn55(n,γ)	U235(n,f)	Pu239(n,f)	Rh103(n,n')	Np237(n,f)	U238(n,f)	In115(n,n')	Fe56(n,p)	Al27(n,alpha)
0.53	0.4 ± 0.4%	0.4 ± 0.3%	0.3 ± 0.1%	0.2 ± 0.1%	0.3 ± 0.1%	-3.7 ± 0.0%	-3.8 ± 0.0%	-4.8 ± 0.1%	-4.8 ± 0.1%	-3.3 ± 0.3%	-2.7 ± 0.4%
2.53	0.9 ± 0.6%	0.5 ± 0.4%	0.2 ± 0.1%	0.0 ± 0.1%	0.1 ± 0.2%	-5.8 ± 0.0%	-6.1 ± 0.0%	-8.0 ± 0.1%	-8.0 ± 0.1%	-5.1 ± 0.3%	-3.9 ± 0.5%
4.53	-0.1 ± 0.8%	-0.4 ± 0.5%	0.5 ± 0.2%	-0.4 ± 0.1%	-0.1 ± 0.2%	-7.6 ± 0.0%	-8.0 ± 0.0%	-10.9 ± 0.1%	-10.9 ± 0.1%	-7.1 ± 0.4%	-5.5 ± 0.6%
6.53	-0.1 ± 1.1%	0.4 ± 0.6%	0.6 ± 0.3%	-0.9 ± 0.1%	-0.4 ± 0.3%	-9.2 ± 0.0%	-9.8 ± 0.0%	-13.2 ± 0.1%	-13.2 ± 0.1%	-9.2 ± 0.5%	-7.2 ± 0.7%
8.53	0.6 ± 1.4%	-0.2 ± 0.7%	-0.4 ± 0.3%	-1.7 ± 0.1%	-1.7 ± 0.3%	-10.6 ± 0.0%	-11.3 ± 0.0%	-15.4 ± 0.1%	-15.3 ± 0.1%	-11.8 ± 0.5%	-9.9 ± 0.8%
10.53	1.2 ± 1.7%	0.8 ± 0.9%	0.6 ± 0.4%	-2.4 ± 0.1%	-2.9 ± 0.3%	-12.1 ± 0.0%	-12.8 ± 0.1%	-17.3 ± 0.1%	-17.3 ± 0.1%	-12.8 ± 0.6%	-10.7 ± 0.9%
12.53	0.2 ± 1.8%	0.9 ± 1.0%	0.0 ± 0.4%	-2.9 ± 0.1%	-3.3 ± 0.3%	-13.2 ± 0.1%	-14.0 ± 0.1%	-18.7 ± 0.1%	-18.7 ± 0.1%	-14.0 ± 0.7%	-11.7 ± 1.0%
14.53	0.4 ± 1.9%	-0.1 ± 1.1%	0.1 ± 0.5%	-3.5 ± 0.1%	-3.8 ± 0.3%	-14.1 ± 0.1%	-14.8 ± 0.1%	-19.6 ± 0.2%	-19.6 ± 0.1%	-14.7 ± 0.7%	-12.5 ± 1.1%
16.53	-0.4 ± 1.9%	-1.3 ± 1.3%	0.2 ± 0.5%	-3.9 ± 0.1%	-4.7 ± 0.2%	-14.8 ± 0.1%	-15.5 ± 0.1%	-20.4 ± 0.2%	-20.6 ± 0.2%	-14.8 ± 0.8%	-11.5 ± 1.2%
18.53	0.8 ± 2.3%	2.6 ± 1.6%	-0.8 ± 0.6%	-4.0 ± 0.1%	-4.6 ± 0.3%	-15.1 ± 0.1%	-15.8 ± 0.1%	-20.8 ± 0.2%	-20.9 ± 0.2%	-14.9 ± 1.0%	-12.3 ± 1.4%

- **Thermal response functions are not affected by the modification of ^{238}U(n,n')**
- **Fast response functions have ^{238}U(n,n') sensitivity coefficients (%/%) greater than 1.0**
  - ➔ A 10 cm attenuation may be sufficient to reach a target accuracy of less than 3% on ^{238}U(n,n')
- **Asymptotic behavior for $\Delta L > 20$cm: sensitivity coefficient of ^{238}U(n,n') remains constant**

DESIGN OF THE EXPERIMENT

Comparison with JEFF-3.1.1 reference: +10% on ^{238}U(n,n) elastic xs

Penetration length (cm)	Au197(n,γ)	In115(n,γ)	Mn55(n,γ)	U235(n,f)	Pu239(n,f)	Rh103(n,n')	Np237(n,f)	U238(n,f)	In115(n,n')	Fe56(n,p)	Al27(n,alpha)
0.53	0.1 ± 0.4%	0.1 ± 0.3%	0.0 ± 0.1%	0.1 ± 0.1%	0.2 ± 0.1%	-0.1 ± 0.0%	0.0 ± 0.0%	0.1 ± 0.1%	0.1 ± 0.1%	0.2 ± 0.3%	0.4 ± 0.4%
2.53	0.1 ± 0.6%	-0.2 ± 0.4%	0.2 ± 0.2%	0.2 ± 0.1%	0.1 ± 0.2%	-0.3 ± 0.0%	-0.3 ± 0.0%	-0.3 ± 0.1%	-0.3 ± 0.1%	-0.3 ± 0.3%	-0.4 ± 0.5%
4.53	-0.7 ± 0.8%	0.0 ± 0.5%	0.3 ± 0.2%	0.1 ± 0.1%	0.0 ± 0.2%	-0.8 ± 0.0%	-0.8 ± 0.0%	-0.6 ± 0.1%	-0.6 ± 0.1%	0.0 ± 0.4%	0.2 ± 0.6%
6.53	0.8 ± 1.1%	0.5 ± 0.6%	0.8 ± 0.3%	0.2 ± 0.1%	0.1 ± 0.3%	-1.4 ± 0.0%	-1.3 ± 0.0%	-0.9 ± 0.1%	-1.0 ± 0.1%	-0.5 ± 0.4%	-0.2 ± 0.7%
8.53	-0.5 ± 1.4%	0.7 ± 0.7%	0.2 ± 0.3%	0.0 ± 0.1%	-0.1 ± 0.3%	-1.8 ± 0.0%	-1.8 ± 0.0%	-1.2 ± 0.1%	-1.3 ± 0.1%	-1.7 ± 0.5%	-1.7 ± 0.7%
10.53	-0.9 ± 1.6%	-0.4 ± 0.9%	0.6 ± 0.4%	-0.3 ± 0.1%	-0.5 ± 0.3%	-2.6 ± 0.0%	-2.5 ± 0.1%	-1.7 ± 0.1%	-1.8 ± 0.1%	-1.7 ± 0.6%	-1.6 ± 0.9%
12.53	-3.4 ± 1.8%	0.2 ± 1.0%	-0.6 ± 0.4%	-0.5 ± 0.1%	-0.8 ± 0.3%	-3.2 ± 0.1%	-3.0 ± 0.1%	-2.1 ± 0.1%	-2.2 ± 0.1%	-1.3 ± 0.7%	-1.4 ± 1.0%
14.53	-0.3 ± 1.8%	0.6 ± 1.1%	1.0 ± 0.5%	-0.8 ± 0.1%	-0.9 ± 0.3%	-3.6 ± 0.1%	-3.5 ± 0.1%	-2.3 ± 0.2%	-2.5 ± 0.1%	-0.9 ± 0.7%	-0.9 ± 1.0%
16.53	-4.0 ± 1.9%	0.1 ± 1.3%	-0.5 ± 0.5%	-1.2 ± 0.1%	-1.3 ± 0.2%	-4.0 ± 0.1%	-3.8 ± 0.1%	-2.5 ± 0.2%	-2.7 ± 0.2%	-0.5 ± 0.8%	0.6 ± 1.1%
18.53	-1.4 ± 2.1%	3.0 ± 1.6%	-0.8 ± 0.6%	-1.2 ± 0.1%	-1.2 ± 0.3%	-4.2 ± 0.1%	-4.0 ± 0.1%	-2.6 ± 0.2%	-2.8 ± 0.2%	-1.1 ± 0.9%	-1.3 ± 1.3%

- **Low sensitivity coefficient to elastic scattering cross section: ~0.1 for responses at E_n > 2MeV**

- **Sensitivity to ^{238}U(n,n) increases linearly with ΔL**

  ➔A compromise should be defined between thr sensitivity to ^{238}U(n,n’) and the one to ^{238}U(n,n)

DESIGN OF THE EXPERIMENT

Comparison with JEFF-3.1.1 reference: +10% on ^{238}U(n,f) fission xs

Penetration length (cm)	Au197(n,γ)	In115(n,γ)	Mn55(n,γ)	U235(n,f)	Pu239(n,f)	Rh103(n,n')	Np237(n,f)	U238(n,f)	In115(n,n')	Fe56(n,p)	Al27(n,alpha)
0.53	0.0 ± 0.4%	0.0 ± 0.3%	0.0 ± 0.1%	0.1 ± 0.1%	0.0 ± 0.1%	0.0 ± 0.0%	0.0 ± 0.0%	0.0 ± 0.1%	0.0 ± 0.1%	0.0 ± 0.3%	0.0 ± 0.4%
2.53	-0.8 ± 0.6%	0.2 ± 0.4%	0.0 ± 0.2%	0.0 ± 0.1%	0.0 ± 0.2%	0.0 ± 0.0%	0.0 ± 0.0%	0.0 ± 0.1%	0.0 ± 0.1%	-0.1 ± 0.3%	-0.2 ± 0.5%
4.53	-0.7 ± 0.8%	-0.7 ± 0.5%	-0.1 ± 0.2%	0.0 ± 0.1%	0.0 ± 0.2%	0.0 ± 0.0%	0.0 ± 0.0%	0.0 ± 0.1%	0.0 ± 0.1%	0.5 ± 0.4%	0.8 ± 0.6%
6.53	-0.7 ± 1.1%	-0.5 ± 0.6%	0.4 ± 0.3%	0.1 ± 0.1%	0.1 ± 0.3%	0.0 ± 0.0%	0.0 ± 0.0%	0.0 ± 0.1%	0.0 ± 0.1%	-0.3 ± 0.4%	0.1 ± 0.7%
8.53	-1.4 ± 1.4%	-0.5 ± 0.7%	-0.3 ± 0.3%	-0.1 ± 0.1%	-0.2 ± 0.3%	0.1 ± 0.0%	0.1 ± 0.0%	0.1 ± 0.1%	0.2 ± 0.1%	-1.1 ± 0.5%	-1.3 ± 0.7%
10.53	-0.4 ± 1.6%	-1.2 ± 0.9%	-0.1 ± 0.4%	-0.2 ± 0.1%	-0.4 ± 0.3%	0.0 ± 0.0%	0.0 ± 0.1%	0.0 ± 0.1%	0.0 ± 0.1%	0.2 ± 0.6%	0.4 ± 0.8%
12.53	1.3 ± 1.9%	0.9 ± 1.0%	-0.4 ± 0.4%	0.0 ± 0.1%	-0.2 ± 0.3%	0.0 ± 0.1%	0.0 ± 0.1%	-0.1 ± 0.1%	0.0 ± 0.1%	0.3 ± 0.7%	0.7 ± 0.9%
14.53	-1.0 ± 1.8%	0.5 ± 1.1%	0.1 ± 0.5%	0.1 ± 0.1%	0.1 ± 0.2%	0.0 ± 0.1%	0.1 ± 0.1%	0.2 ± 0.2%	0.2 ± 0.1%	-0.4 ± 0.7%	-0.7 ± 1.0%
16.53	1.5 ± 1.9%	-1.0 ± 1.3%	-0.3 ± 0.5%	0.0 ± 0.1%	-0.2 ± 0.2%	0.1 ± 0.1%	0.1 ± 0.1%	0.2 ± 0.2%	0.2 ± 0.2%	1.1 ± 0.8%	1.8 ± 1.1%
18.53	3.3 ± 2.3%	0.9 ± 1.6%	-0.1 ± 0.6%	0.2 ± 0.1%	0.6 ± 0.3%	0.1 ± 0.1%	0.1 ± 0.1%	0.2 ± 0.2%	0.2 ± 0.2%	0.4 ± 0.9%	0.5 ± 1.3%

- **Negligible sensitivity to ^{238}U fission cross section**

➔ **Conclusion: propagation through a ^{238}U block of thickness 15-20cm is optimal for ^{238}U(n,n')**

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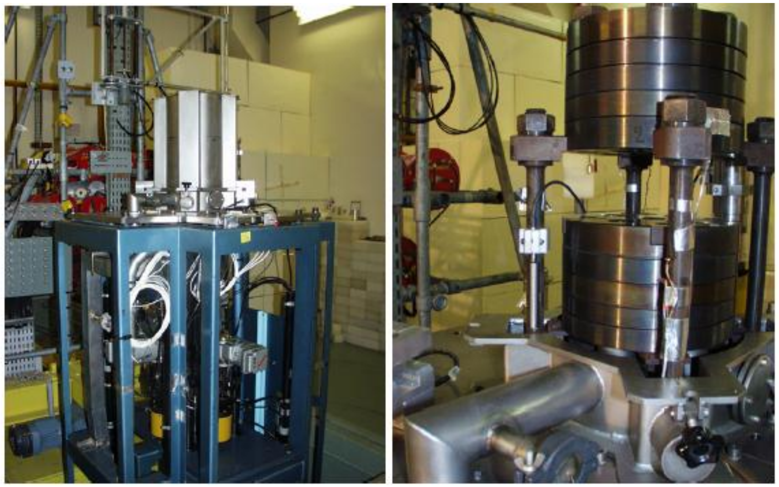
- Design of the Experiment
- **EXCALIBUR program**
- Conclusions and prospects

EXCALIBUR PROGRAM

- **Overview of available facilities in CEA (2013)**
  - Irradiation facilities using neutron sources (D-T / D-D generators, ^{252}Cf)
    → Neutron flux intensity too low
  - Zero Power Mock-Up Reactors: EOLE (Thermal), MINERVE (Thermal), MASURCA (Fast)
    → Unavailable due to ongoing programs till 2016
  - Pulse Fast Reactor: CALIBAN
    → 1 week of beam time / year

- **Bare Highly Enriched Uranium Fast Reactor CALIBAN (same as GODIVA in the US)**
  - 2 blocks of 5 disks (ϕ = 19.5cm, h=2-3cm)
  - UMo(10%) with 93.5% ^{235}U/U
  - Pulse mode (nominal), power step mode

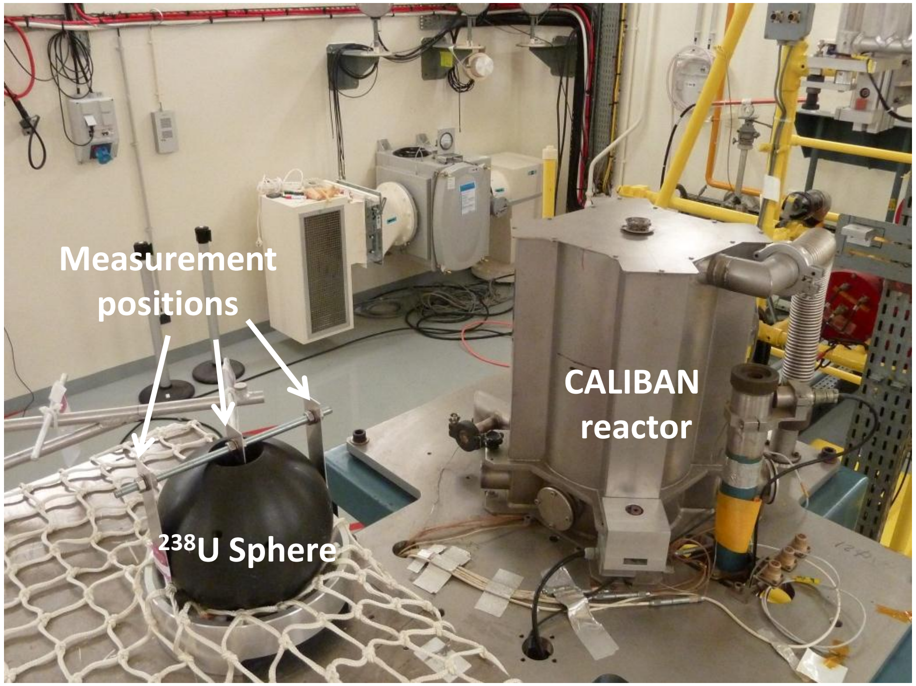


- **The project « EXCALIBUR » was settled in 2013 within the CEA/DEN and CEA/DAM collaboration on nuclear data:**
  EXperiment in CALIBAN on URanium 238

- **Financial support of industrial partners EDF and AREVA in 2015**

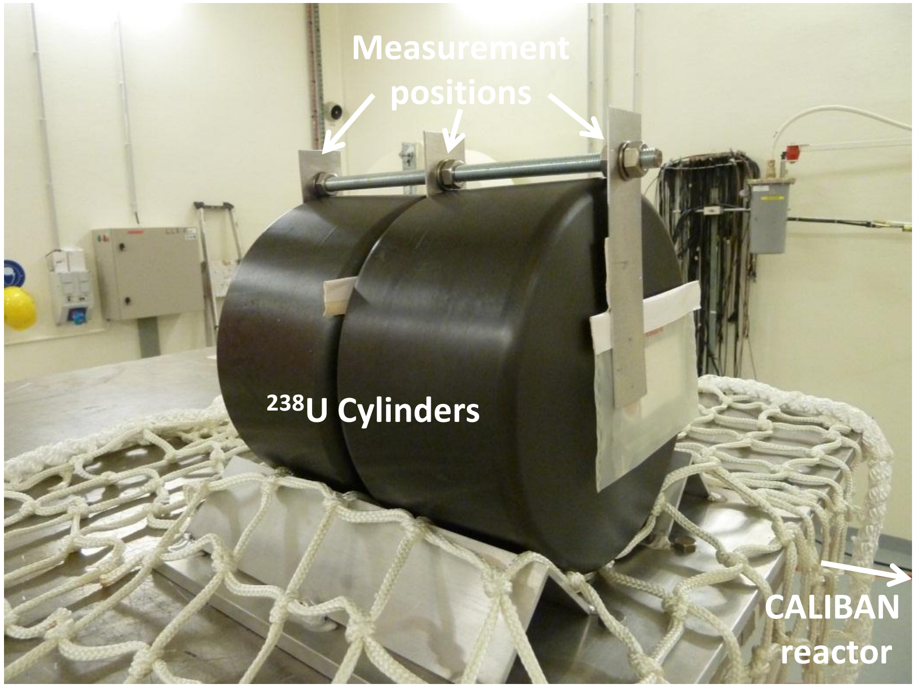
EXCALIBUR PROGRAM
2 experimental campaigns

Sphere Experiment (january 2014)



- 1 sphere (ϕ = 17cm) with a central cavity (ϕ = 5cm)
- Metallic ^{nat}U with 0.2% impurities and 1.5% Mo
- 3 measurements positions (~7cm and 14cm attenuation)
- Mean distance 63cm to the reactor z-axis

Cylinder Experiment (october 2014)



- 2 cylinders (ϕ = 18cm, h=9cm)
- Metallic ^{nat}U with 0.3% impurities
- 3 measurements positions (9cm and 18cm attenuation)
- Mean distance 61cm to the reactor z-axis

EXCALIBUR PROGRAM
Details of the experiment

- **2 irradiations / campaign:**
  - 600W x 2hours
  - Incident fluence on ^{238}U device: 8-9.10^{12} n.cm^{-2}

- **Dosimeter list covering thermal (< 1 MeV) to high energy range (>5 MeV)**

- **γ-spectrometry measurements on [HP]Ge**
  - Target statistical uncertainty: less than 1% (1σ)
  - At least 2 countings / dosimeter (⇨ repeatability)
  - Redundant countings on some dosimeters between 3 labs: CEA-DAM (Valduc), CEA-DEN (Cadarache) and CNRS-LPSC (Grenoble) (⇨ reproducibility)
  - Redundant dosimeters between the two campaigns (⇨ reliability)

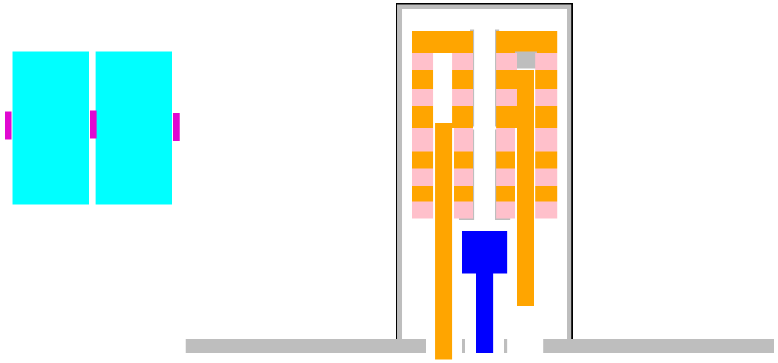
Dosimeter	Target reaction	Diam. [mm]	Thick. [mm]	E50% [MeV]	Period
Au	^{197}Au(n,γ)^{198}Au	20	0.01	0.72	2.3d
Fe	^{58}Fe(n,γ)^{59}Fe	20	2.0	0.73	44d
U8	^{238}U(n,γ)^{239}Np	12.1	0.1	0.92	2.4d
In	^{115}In(n,γ)^{116m}In	20	0.125	1.1	54min
U5	^{235}U(n,f)FP	12.1	0.1	1.71	•
Rh	^{103}Rh(n,n')^{103m}Rh	20	0.05	2.38	56min
In	^{115}In(n,n')^{115m}In	20	0.125	2.67	4.5h
U8	^{238}U(n,f)FP	12.1	0.1	2.78	•
Ti	^{47}Ti(n,p)^{47}Sc	20	2.0	3.82	3.3d
Ni	^{58}Ni(n,p)$^{58(g+m)}$Co	20	2.0	4.20	70.9d
Fe	^{54}Fe(n,p)^{54}Mn	20	2.0	4.28	312.1d
Ti	^{46}Ti(n,p)^{46}Sc	20	2.0	6.08	83.8d
Fe	^{56}Fe(n,p)^{56}Mn	20	2.0	7.58	2.6h
Mg	^{24}Mg(n,p)^{24}Na	20	2.0	8.26	15h

- **Measurement procedure: only relative γ-activities to cancel uncertainties due to**
  - Detector efficiency
  - Irradiation time and power
  - γ-emission intensity and (half-life)

EXCALIBUR PROGRAM
Ongoing work

- **Measurement report is expected for june 2015**

- **Interpretation will be performed with the TRIPOLI4 continuous energy Monte-Carlo code**
  - Core geometry based on ICSBEP HMF-080
  - Additionnal modeling: concrete walls, table, dosimeter holder, plastic bags…



- **Huge computing time**
  - One configuration requires 50 000 h.CPU to reach <2% uncertainty on reaction rate ratii
  - 4 configurations to be calculated

  ➔ Simplifications are required to gain on computing time (2 step global/local calculation)

- **Sensitivities to be calculated by perturbation method (correlated sampling)**
  - 33-group structure
  - Mainly ^{238}U(n,n’), ^{238}U(n,n), ^{238}U(n,f) cross sections
  - Test of various PFNS for ^{235}U

- **Trends and *a posteriori* covariances will be provided with the Integral Data Assimilation (IDA) technique in CONRAD**

OUTLINE

- Context
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- EXCALIBUR program
- Preliminary results
- **Conclusions and prospects**

CONCLUSIONS AND PROSPECTS

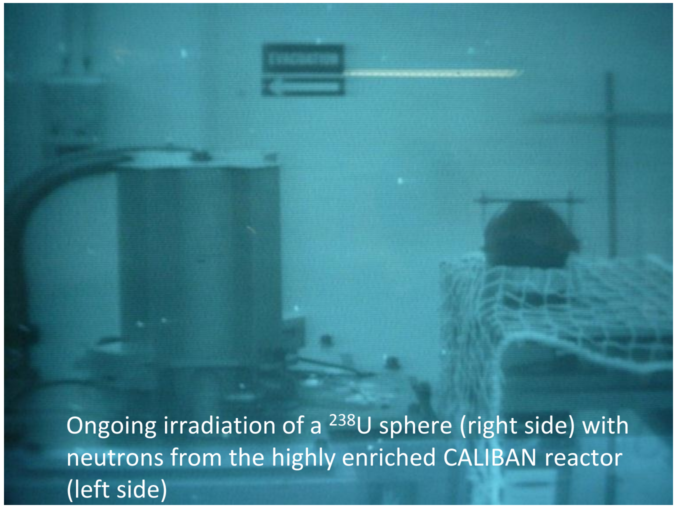
- Inelastic scattering of ^{238}U has a significant impact in many fields of reactor physics (LWR, FR) and may affect several key-parameters: power map, absorber efficiency, kinetics parameters, Na void effect, doppler…

- No concensus on the covariance to be adopted in the 2-5 MeV range of maximum sensitivity for reactor applications:
  - ⇨s.d. ranging from 5 to 20% (1σ)

- Consistent trends derived from a set of independant integral experiments:
  - ⇨Probable overestimation of ^{238}U(n,n’) by ~10% in JEFF-3.1.1

- A transmission experiment was designed and performed in the CALIBAN reactor
  - ⇨ 2 different ^{238}U devices
  - ⇨ 14 dosimeters with responses covering 0.7-8.3 MeV
  - ⇨ Experimental uncertainties <3% (1σ)

- Experimental reported is ongoing with first trends on ^{238}U(n,n’) to be reported by the end of 2015


Ongoing irradiation of a ^{238}U sphere (right side) with neutrons from the highly enriched CALIBAN reactor (left side)

THANK YOU
FOR YOUR ATTENTION

Acknowledgments to

- CEA/DAM team on CALIBAN for setting-up the experiment
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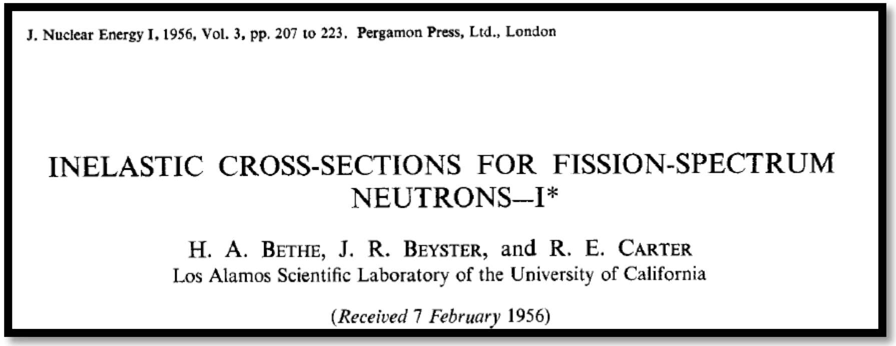
DESIGN OF THE EXPERIMENT
Experimental data related to ^{238}U(n,n')

- **Same idea than H. Bethe experiments**



J. Nuclear Energy I, 1956, Vol. 3, pp. 207 to 223. Pergamon Press, Ltd., London

INELASTIC CROSS-SECTIONS FOR FISSION-SPECTRUM NEUTRONS—I*

H. A. Bethe, J. R. Beyster, and R. E. Carter
Los Alamos Scientific Laboratory of the University of California

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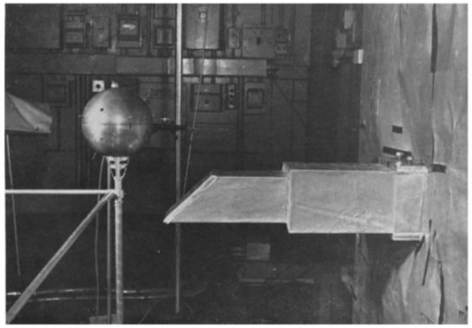

Fig. 9.2.—External collimator with source and a typical 8-inch (outside diameter) sphere on its supporting cone.

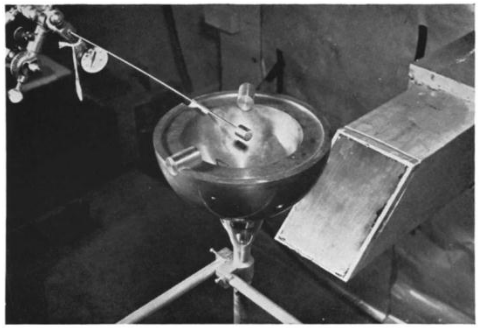

Fig. 9.3.—Source plate and a spiral counter in position at the centre of a hemisphere.

- **Transmission through a sphere of pure material is linked to the inelastic xs:**

$$T(X) = F(X)e^{-\sigma_{in}X}$$

-> *F(X)* accounts for multiple scatterings

➔ Reduced degree of freedom compared with other integral experiments
  - **much smaller sensitivity to the prompt fission neutron spectrum**
  - **negligible contributions from ^{235}U or ^{239}Pu cross sections**