Neutron capture measurements with the n_TOF Total Absorption Calorimeter at CERN

D. Cano-Ott, A. García, E. González, C. Guerrero*, T. Martínez, E. Mendoza, M. C. Ovejero, J. Tera, D. Villamarín
(The n_TOF Collaboration)

CIEMAT, Unidad de Innovación Nuclear

carlos.guerrero@ciemat.es

*Now at CERN PH/SME

Outline

1. The need of advanced nuclear reactors for a sustainable energy production and minimization of the nuclear waste

2. Research lines at the CIEMAT Nuclear Innovation Unit

3. Neutron capture measurements of Actinides at n_TOF
    1. The n_TOF facility @ CERN
    2. The Total Absorption Calorimeter (TAC)
    3. Past, present and future s(n,g) measurements on Actinides

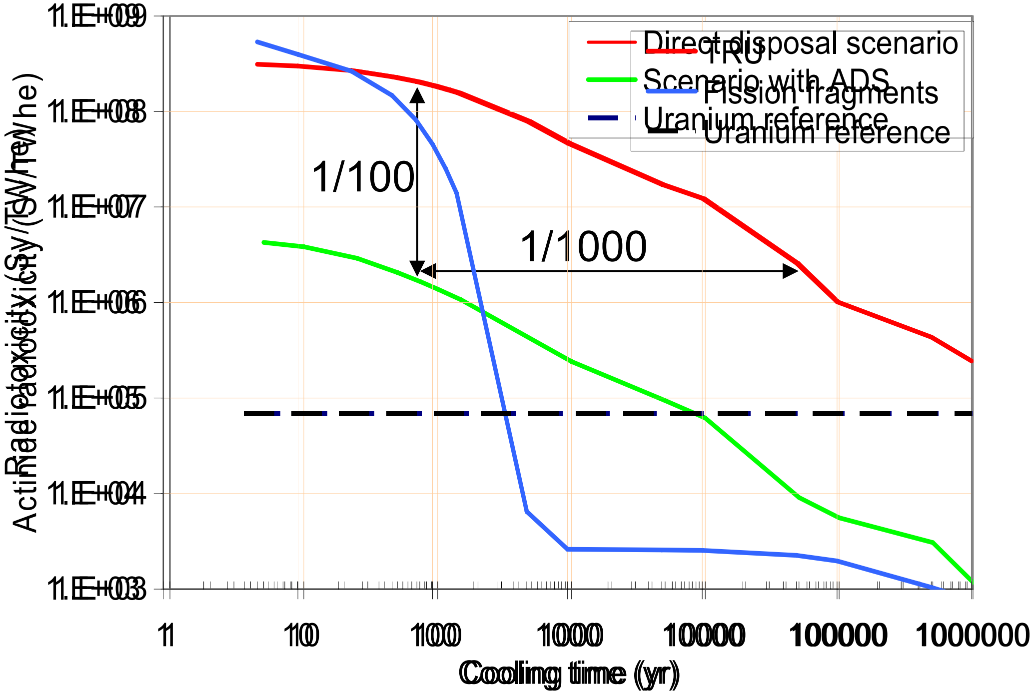
4. Summary

The need of Advanced Nuclear Reactors

Nuclear energy provides almost 20% of the worldwide electricity demand (~30% in the EU):

439 Nuclear Reactors operating worldwide in 2008

197 Nuclear Reactor in the EU, where 13 more are under construction.



Management of HLW

Deep Underground Repository

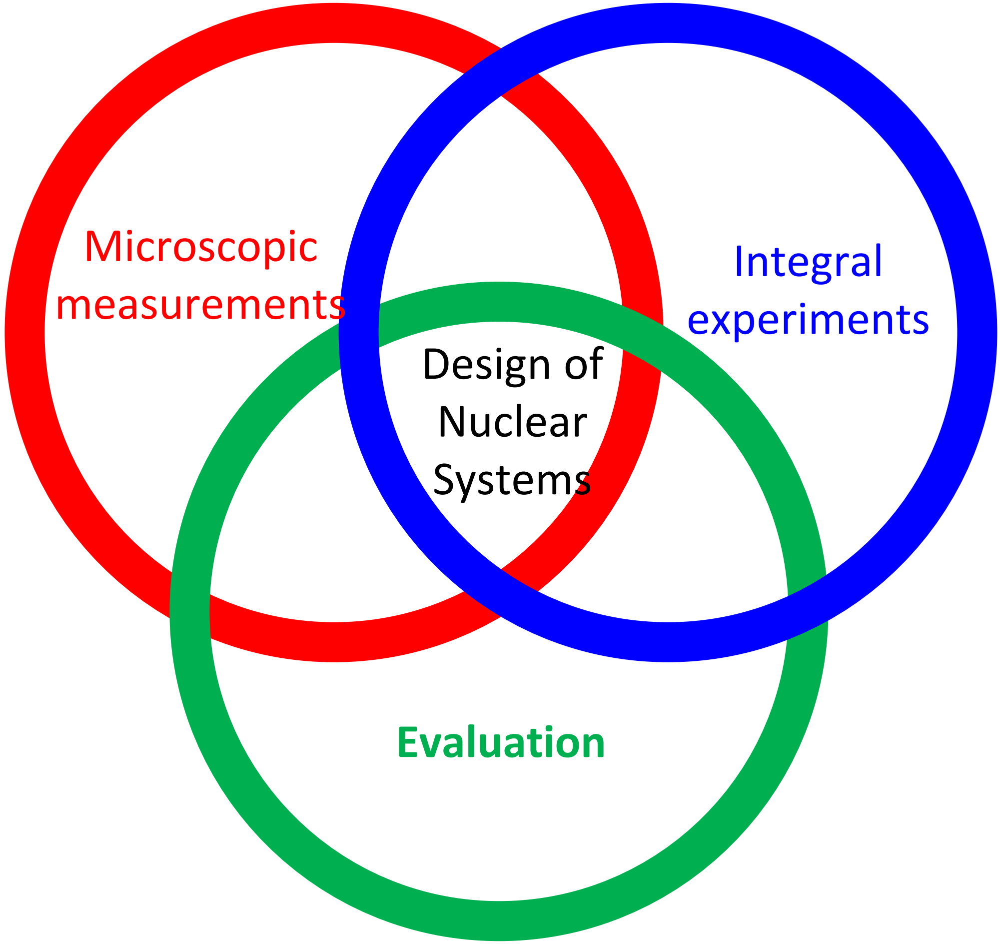
It would be preferable to reduce the number of repositories and/or their volumes.

<u>Design and construction of advanced nuclear reactors:</u>
optimized fuel cycle, increased safety, reduced-production/incineration of nuclear waste, …

Design of Advanced Nuclear Reactors

Significant differences with respect to present commercial reactors:

- New fuel composition: U, Pu and Minor Actinides
- Different neutron energy spectrum: fast (keV, MeV) vs. thermal (meV, eV)
- Subcritical instead of critical in the case of ADS.



La *Unidad de Innovación Nuclear* del CIEMAT

DATOS NUCLEARES PARA LA TRANSMUTACIÓN Y REACTORES AVANZADOS

Medidas de datos nucleares necesarios para el diseño y evaluación de reactores críticos y subcríticos avanzados.

- *MICINN: Plan Nacional de Física de Partículas*
- *PROYECTOS DEL 6º y 7º PM DE LA UE: IP-EUROTRANS/NUDATRA, CANDIDE, ANDES, ENSAR*

EXPERIMENTOS INTEGRALES EN REACTORES SUBCRÍTICOS

Estudios experimentales en reactores avanzados subcríticos para la transmutación de residuos radiactivos, profundizando en los procesos físicos que controlan dichos reactores.

- *PROYECTOS DEL 6º Y 7º PM DE LA UE: IP-EUROTRANS/ECATS(YALINA-BOOSTER, GUINEVERE), FREYA*

CICLOS AVANZADOS DEL COMBUSTIBLE NUCLEAR

Evaluación y optimización de ciclos avanzados del combustible nuclear con reciclado de plutonio y, posiblemente, de actínidos minoritarios y productos de fisión.

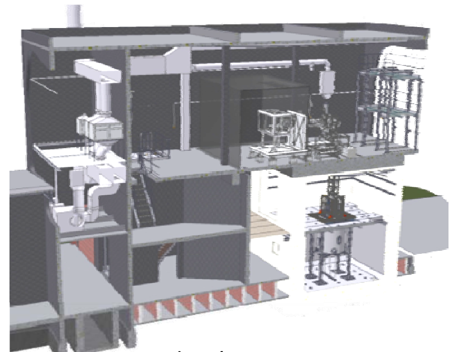
- *PROYECTOS DEL 6º Y 7º PM DE LA UE: RED-IMPACT, PATEROS, IP-EUROTRANS, ARCAS*
- *Plataforma SNE-TP*
- *Participación en el grupo WPPT de la AEN/OCDE*

REACTORES CRÍTICOS Y SUBCRÍTICOS

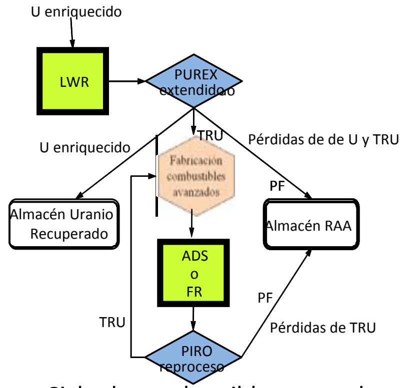
Evaluación de diseños de reactores críticos y subcríticos avanzados, experimentales y prototipos, tanto de espectro rápido como térmico.

- *PROYECTO DEL 6º PM DE LA UE: MTRI3, CP-ESFR, CDT-FASTEF*
- *Jules Horowitz reactor*

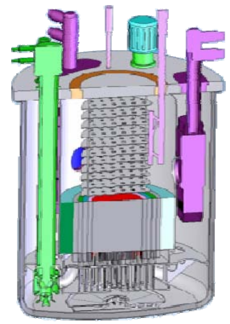
Todas las líneas de investigación son financiadas dentro del ACUERDO CIEMAT-ENRESA



Instalación GUINEVERE



Ciclo de combustible avanzado



Diseño del Reactor Europeo de Sodio

Datos Nucleares para la Transmutación y Reactores Avanzados

Estudio de la emisión de neutrones retardados:

1. Medidas de la emisión de neutrones retardados en la desintegración beta de F.F. en FAIR.
2. Diseño y construcción de un espectrómetro de neutrones por tiempo vuelo para determinar la energía y probabilidad de emisión de neutrones retardados.
3. Desarrollo de sistemas de adquisición de datos digitales.

Simulaciones Monte Carlo:

1. Diseño de instalaciones con fuentes de neutrones (n_TOF, ESS Bilbao)
2. Desarrollo de códigos de simulación MC para detectores de rayos gamma y neutrones.
3. Desarrollo de software para utilizar en GEANT4 cualquier librería de secciones eficaces evaluadas.

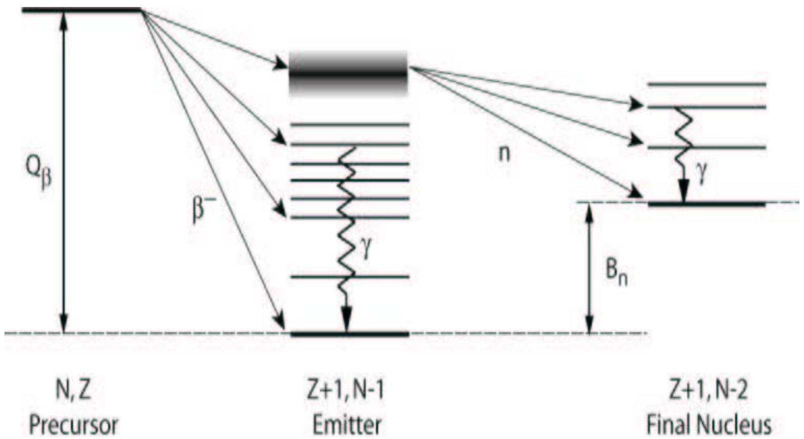
Medidas de secciones eficaces neutrónicas (n,γ) y (n,f) de elementos transuránicos (n_TOF/CERN):

1. Propuesta, preparación y realización de experimentos.
2. Desarrollo de software de análisis: calculo de eficiencia, correcciones de fondo, tiempo muerto, pile-up, etc.
3. Análisis y evaluación de secciones eficaces de captura en las zonas de resonancias resueltas y no resueltas.

Datos Nucleares para la Transmutación y Reactores Avanzados

Estudio de la emisión de neutrones retardados:

1. Medidas de la emisión de neutrones retardados en la desintegración beta de F.F. en FAIR y en Cyclotron Laboratory of the University of Jyvaskyla (ver charla de B. Gómez el miércoles).
2. Diseño y construcción de un espectrómetro de neutrones por tiempo vuelo para determinar la energía y probabilidad de emisión de neutrones retardados.
3. Desarrollo de sistemas de adquisición de datos digitales.



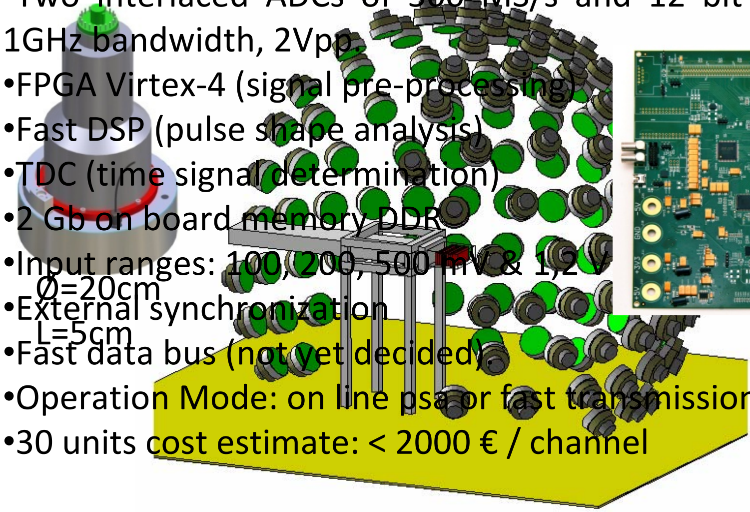
Contribuyen a la estabilidad de los reactores y a la emision de calor.

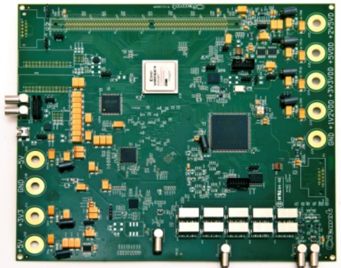
IDEAL NEUTRON TOF SPECTROMETER DESIGN

High ε_n | n-□ discrimination
Improved ΔE/E | cross-talk rejection
Lowest threshold | Digital electronics

DIGITISER DESIGN (Colaboración con la Unidad de Electrónica del CIEMAT, J. Marín y J. Castilla)

- Two interlaced ADCs of 500 MS/s and 12 bit resolution, 1GHz bandwidth, 2Vpp.
- FPGA Virtex-4 (signal pre-processing)
- Fast DSP (pulse shape analysis)
- TDC (time signal determination)
- 2 Gb on board memory DDR2
- Input ranges: 100, 200, 500 mV & 1, 2 V
- External synchronization
- Fast data bus (not yet decided).
- Operation Mode: on line psa or fast transmission
- 30 units cost estimate: < 2000 € / channel





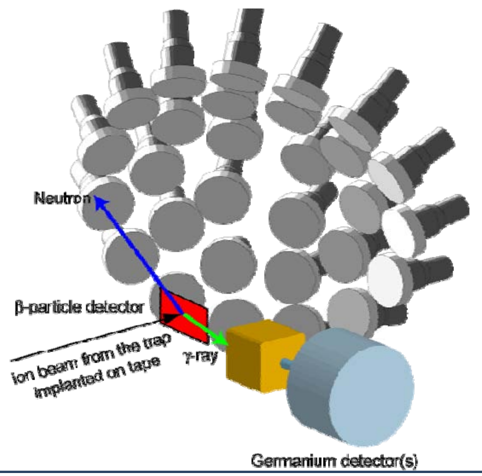
- La celda prototipo ya ha sido irradiada en PTB (Alemania)
- El próximo año se probará en Jyvaskyla (Finland) un espectrómetro prototipo con 30 celdas

Datos Nucleares para la Transmutación y Reactores Avanzados

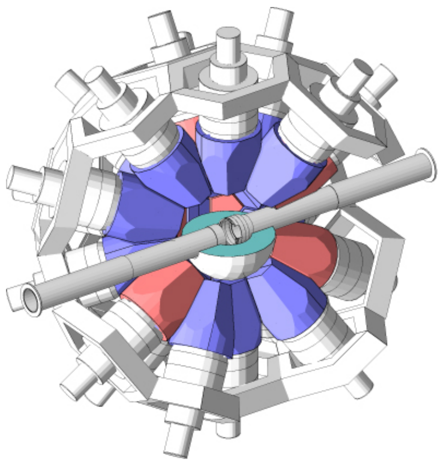
Simulaciones Monte Carlo:

1. Desarrollo de códigos de simulación MC para detectores de rayos gamma y neutrones.
2. Diseño de instalaciones con fuentes de neutrones (n_TOF, ESS Bilbao)
3. Desarrollo de software para utilizar en GEANT4 cualquier librería de secciones eficaces evaluadas.

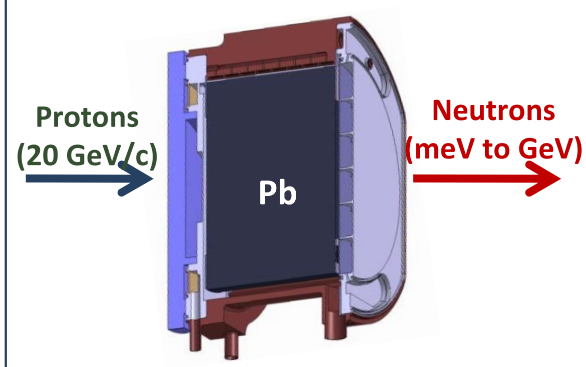
Detección de neutrones



Detección de rayos gamma



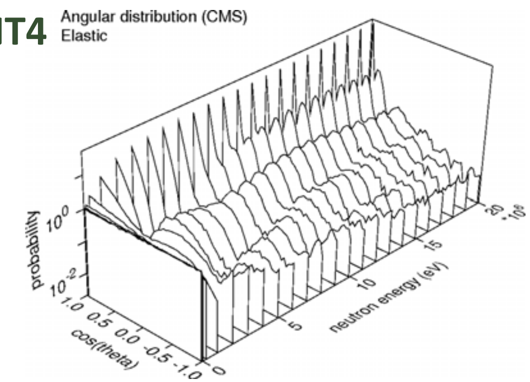
Producción de neutrones por espalación



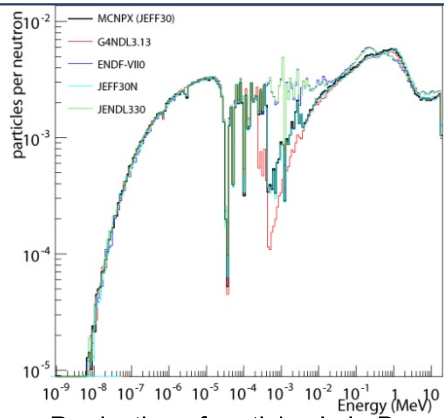
Librerías de secciones eficaces para GEANT4

No solo secciones eficaces de cualquier libreria, sino toda la informacion en ENDF: produccion de secundarios, distribuciones de energia, correlaciones angulares, etc.

Disponible CD con librerías, manual y gráficos.



Angular distribution of outgoing neutrons in $^{235}U(n,el)$ in (ENDF/B-VII.0)

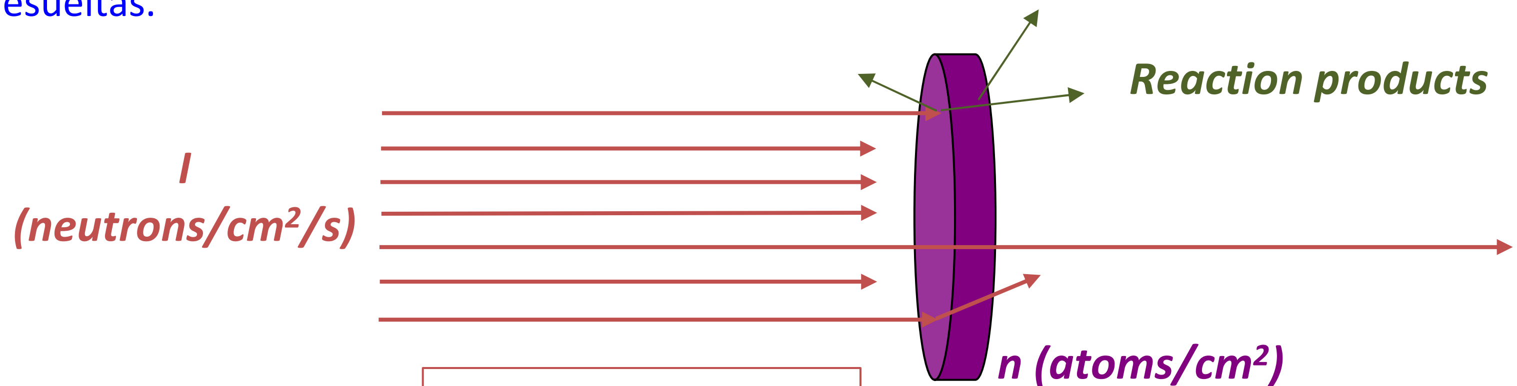


Production of particles in $LaBr_3$ under neutron bombardment

Datos Nucleares para la Transmutación y Reactores Avanzados

Medidas de secciones eficaces neutrónicas (n,γ) y (n,f) de elementos transuránicos (n_TOF/CERN):

1. Propuesta, preparación y realización de experimentos.
2. Desarrollo de software de análisis: calculo de eficiencia, correcciones de fondo, tempo muerto, pile-up, etc.
3. Análisis y evaluación de secciones eficaces de captura en las zonas de resonancias resueltas y no resueltas.



$$R = \sigma \cdot I \cdot n$$

Measuring the neutron cross sections requires:

- A facility providing a neutron beam (The n_TOF facility).

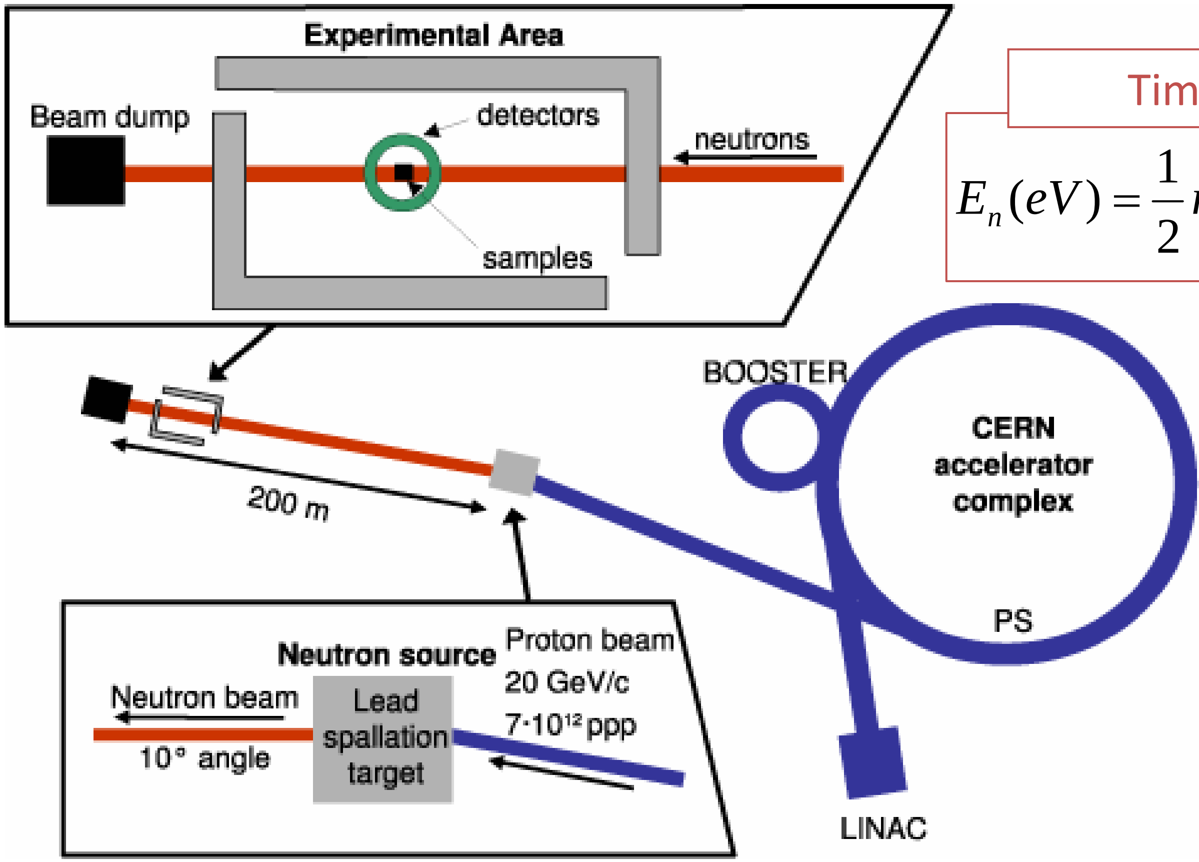
- A detection system for counting the reactions (The TAC).

- A highly pure sample.

- The analysis tools to determine the measured cross section with the required accuracy (few %)

The n_TOF facility at CERN

The n_TOF facility: built in 1999-2000 by the n_TOF Collaboration (>20 institutions and >100 scientists) for measuring accurate capture and fission cross sections relevant for transmutation of nuclear waste and nuclear astrophysics.



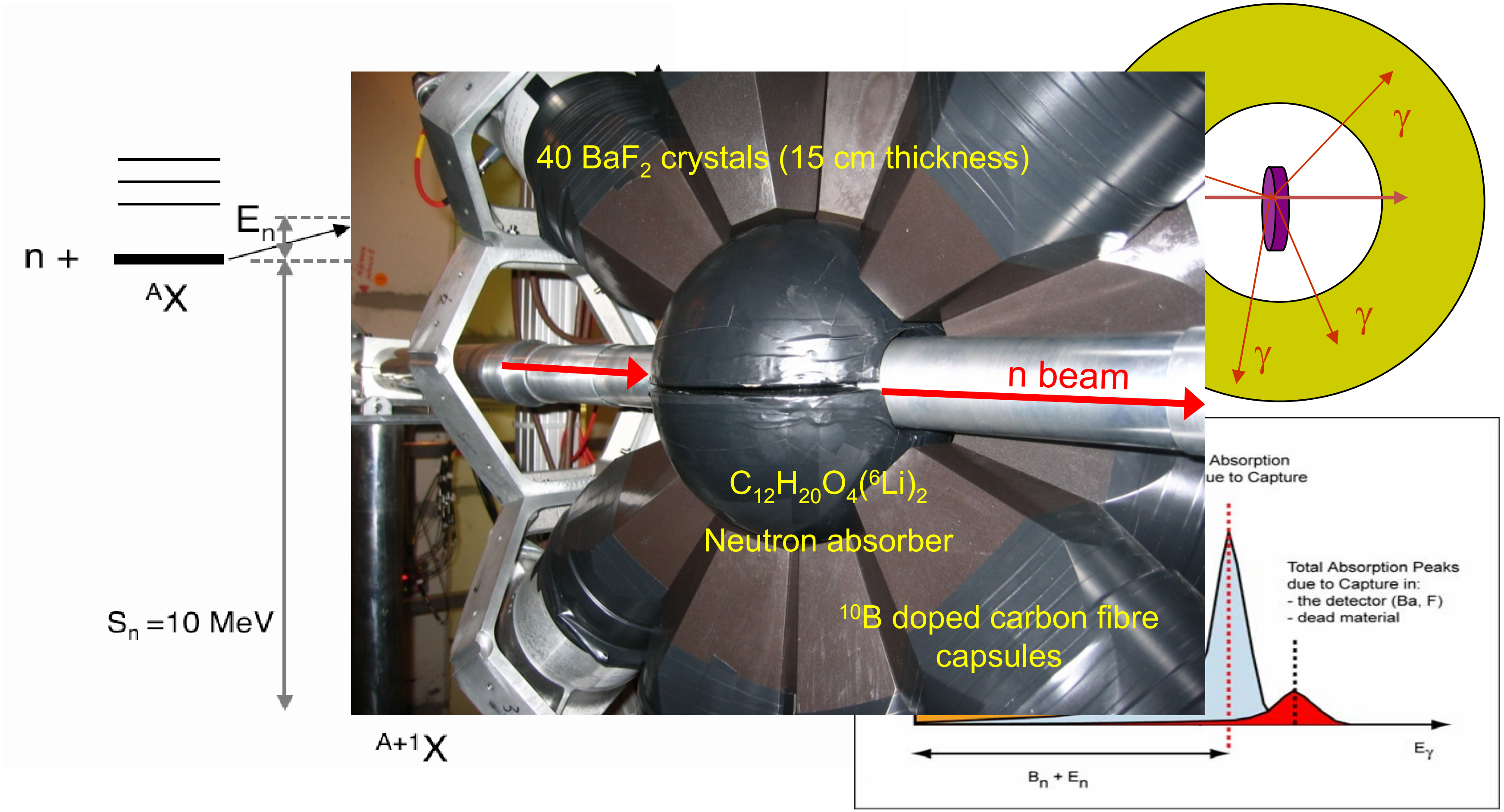
Time-of-Flight technique

$$E_n(eV) = \frac{1}{2} m_n v^2 = \frac{1}{2} m_n \left(\frac{L(m)}{t_{det}(\mu s) - t_0(\mu s)} \right)^2$$

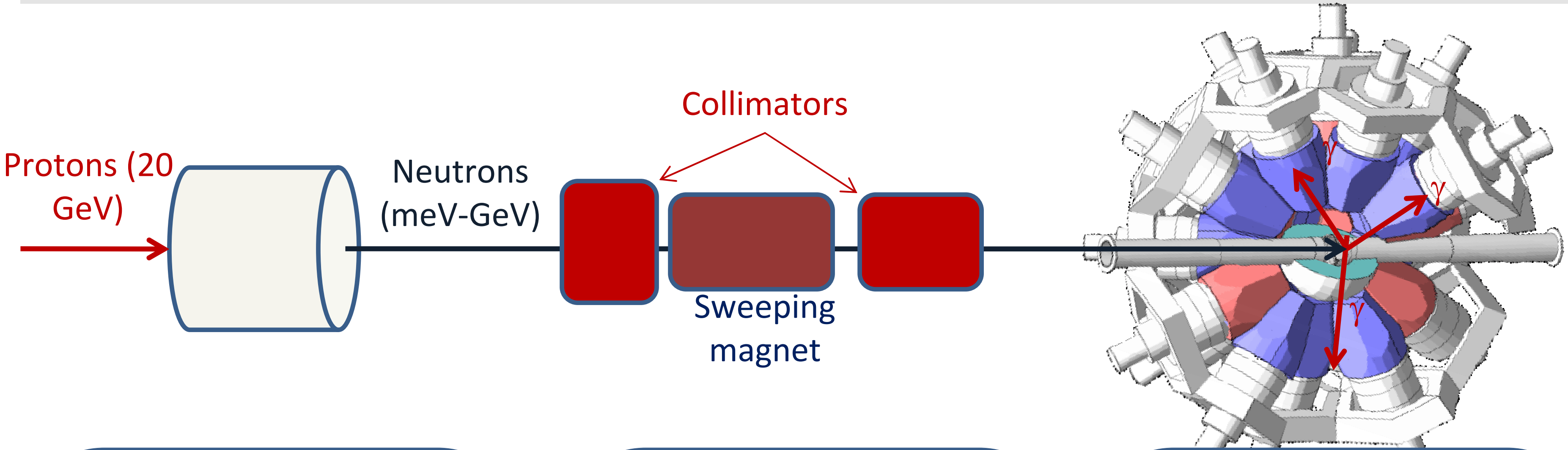
The n_TOF Total Absorption Calorimeter (TAC)

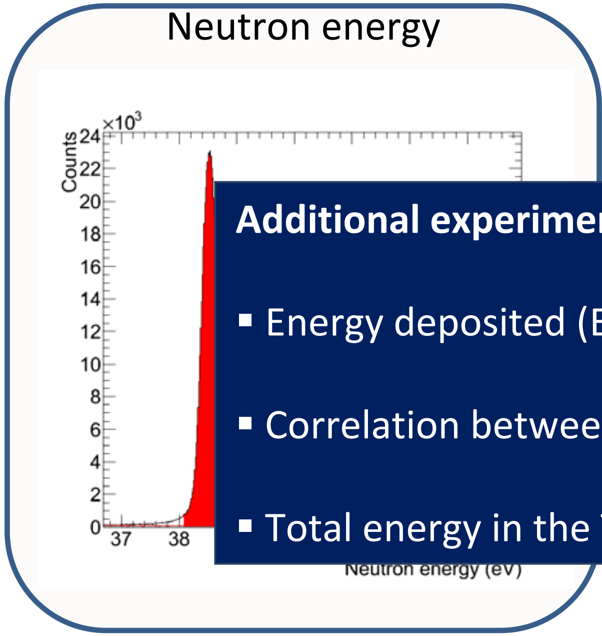
Detecting capture reactions means to detect the subsequent EM cascade.

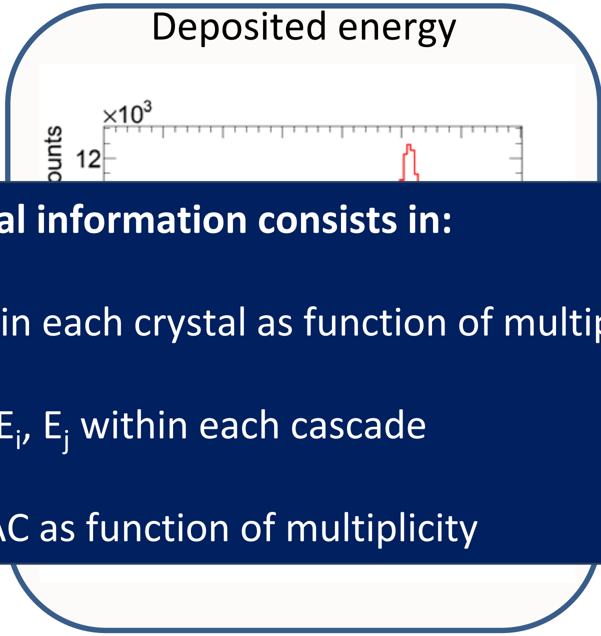
The best suited technique for the detection of capture cascades in the measurement of low-mass/radioactive samples is the total absorption technique.

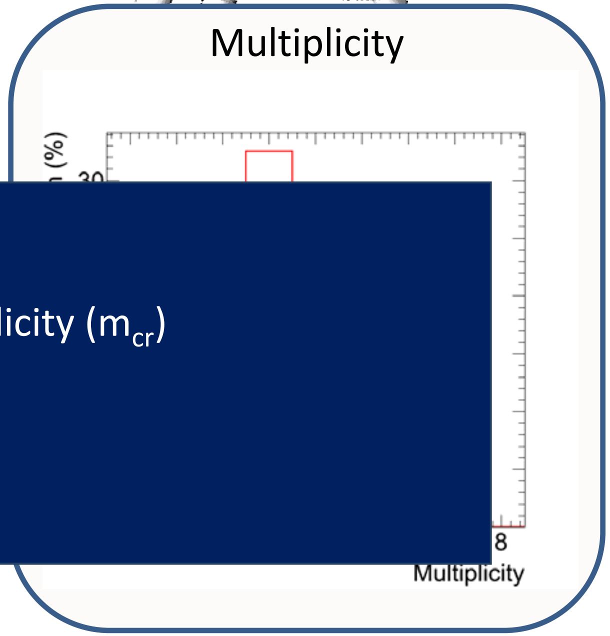


Detection of (n,γ) cascades with the n_TOF/TAC





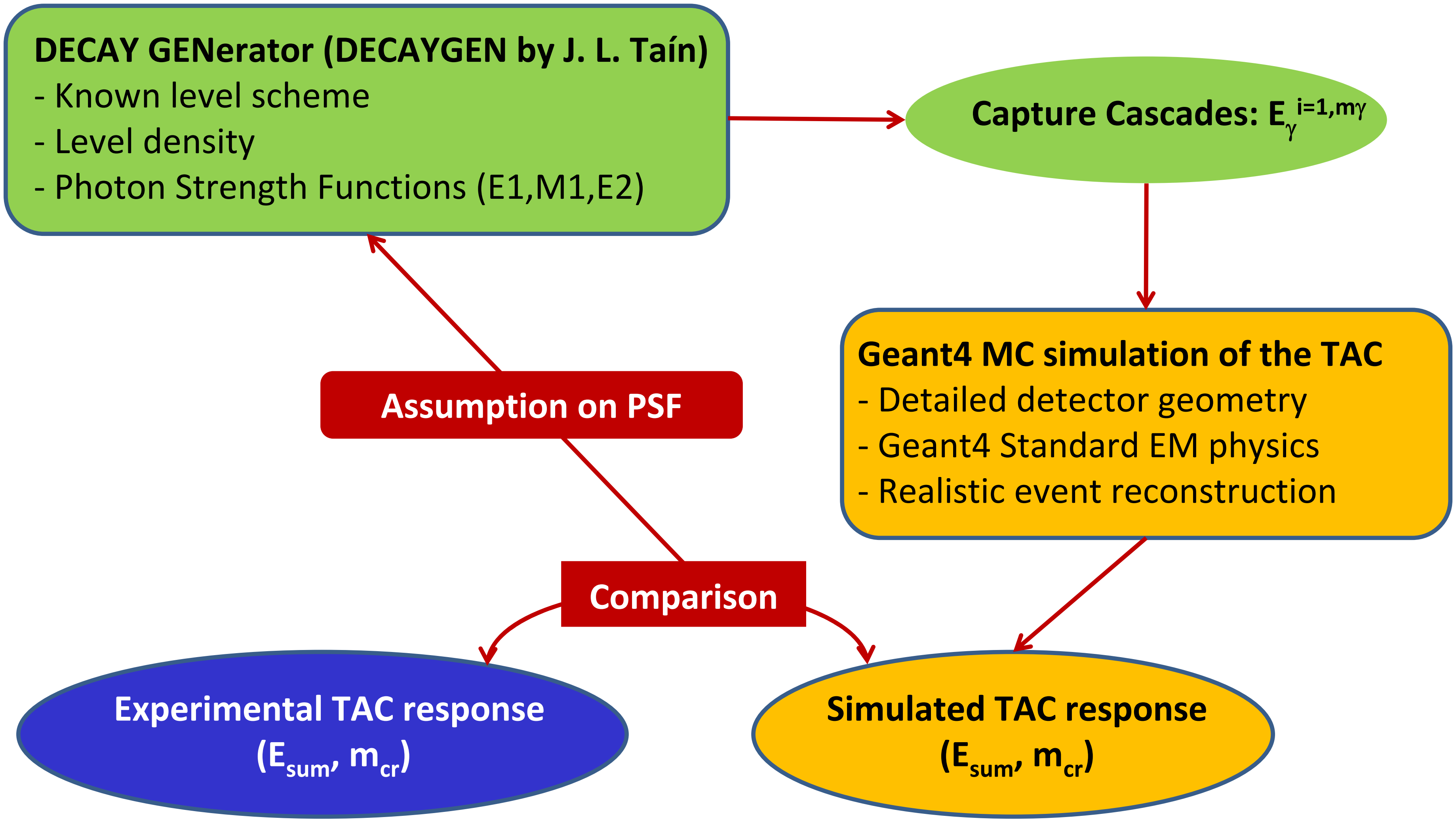




Additional experimental information consists in:

- Energy deposited (E_i) in each crystal as function of multiplicity (m_{cr})
- Correlation between E_i, E_j within each cascade
- Total energy in the TAC as function of multiplicity

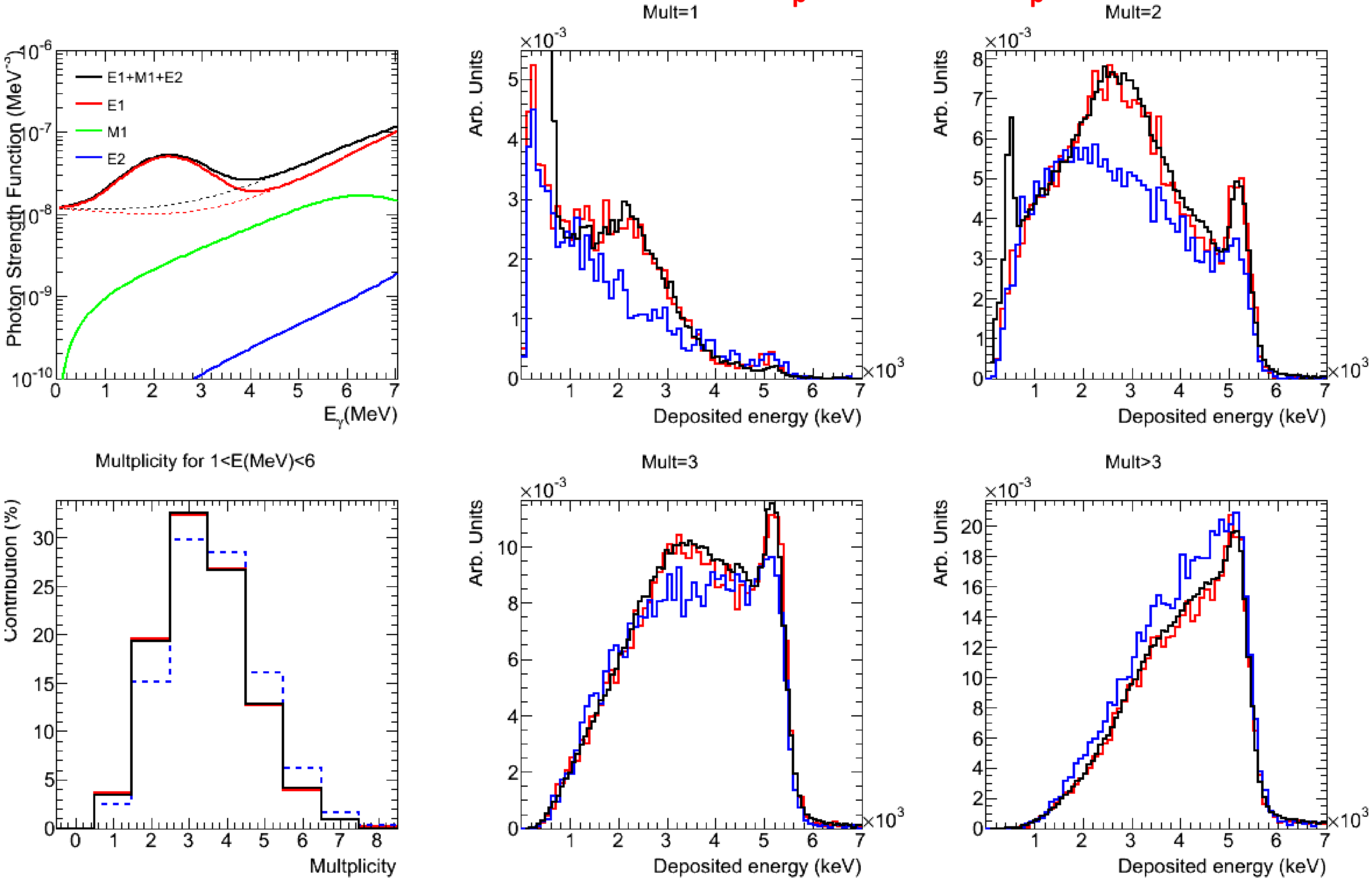
Study of PSF with the n_TOF/TAC by means of MC simulations



Study of PSF: ^{241}Pu

PSF from RIPL-2 + PYGMY E1 (E_p=2.3 MeV, Γ_p=0.75 MeV)

PSF from RIPL-2



GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

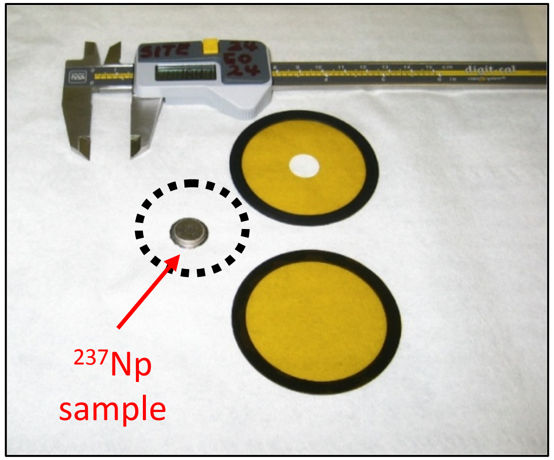
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

C. Guerrero et al. @ EFN 2010
27-29 Septiembre 2010, El Escorial - Madrid

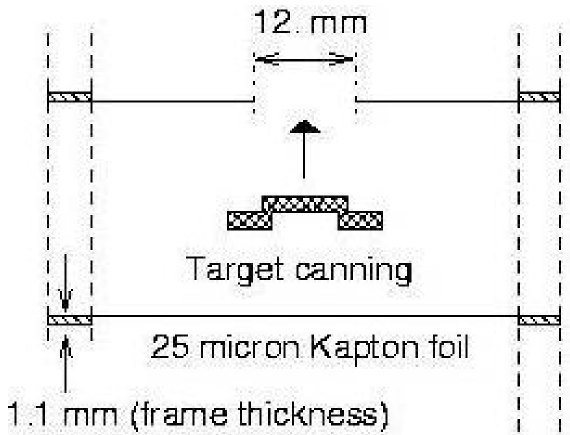
CERN
TOF

Capture cross section on actinides at n_TOF

Sample	Mass (mg)	E_n	Status
^{233}U	91.0	< 2 keV	Delayed due to difficulties with (n,f) background
^{234}U	32.7		Complete
^{237}Np	43.3		Complete
^{240}Pu	51.2		Complete
^{243}Am	10.0		Complete
^{241}Am	32.3	<25 keV	Ongoing (Sept-Oct 2010)
^{235}U*	3.0	1-10 eV	Scheduled for October 2010 (fission tagging test)
^{238}U	700	?	Scheduled for April 2011



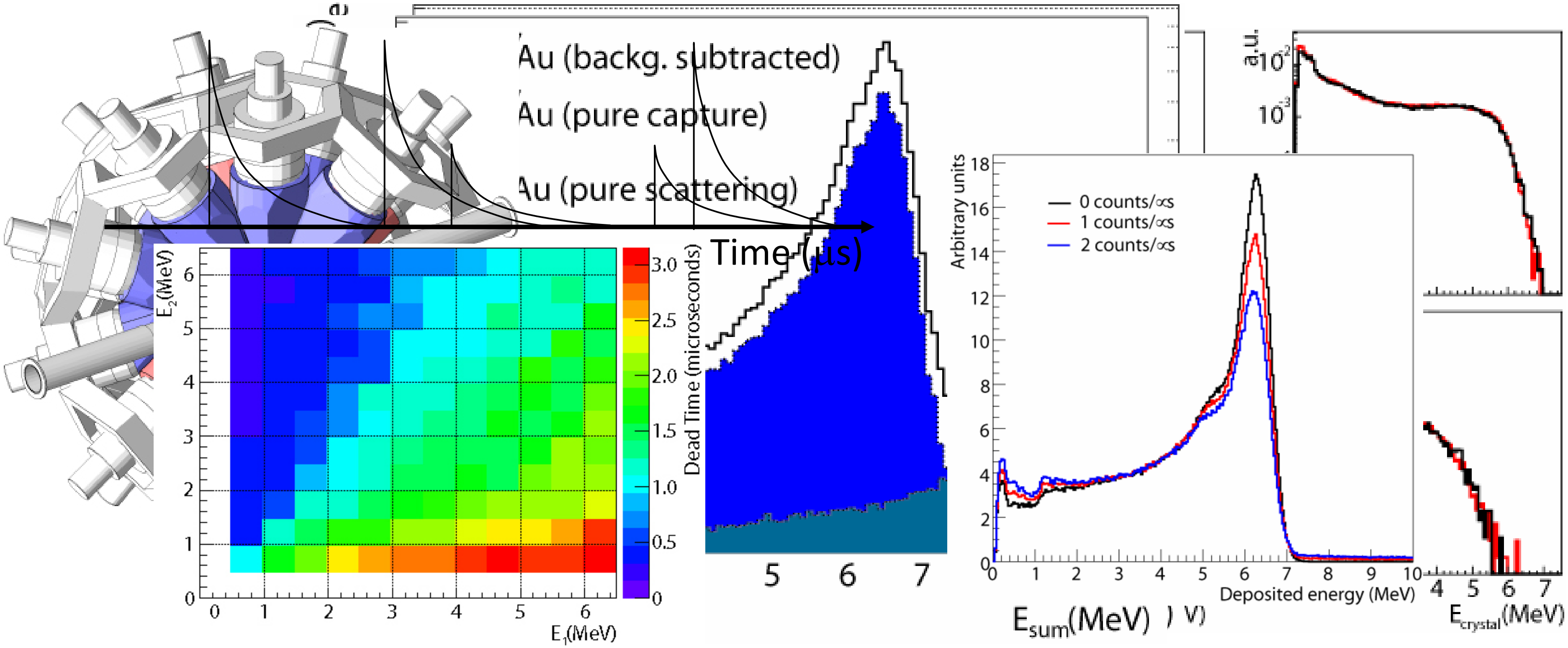
All samples had 1 cm diameter



The Ti capsule limited the high energy frontier to 2 keV

σ(n,γ) measurements with the TAC: Obtention of the Capture Yield

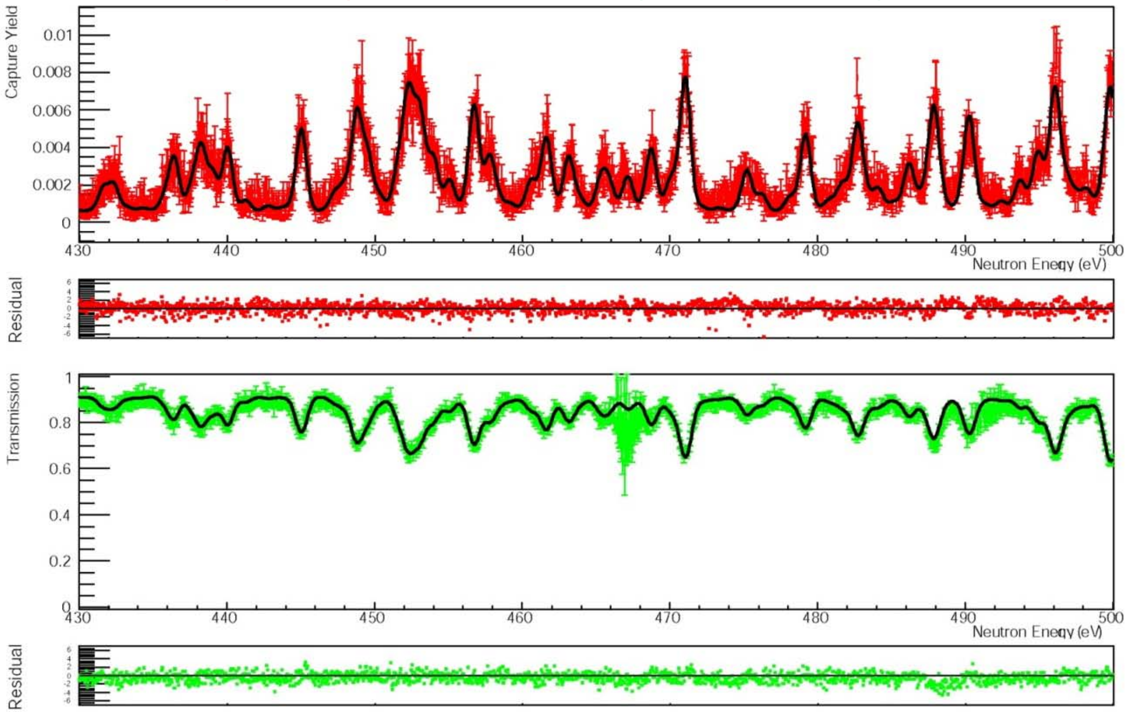
1. Selection of the optimum conditions in E_{sum} & m_{cr}
2. Background determination: beam-off, beam-on (empty, dummy-sample, etc).
3. (n,n) background: experimental determination by comparison with Carbon sample.
4. Detection efficiency: Geant4 MC simulations.
5. Correction of dead-time, pile-up and summing effects.



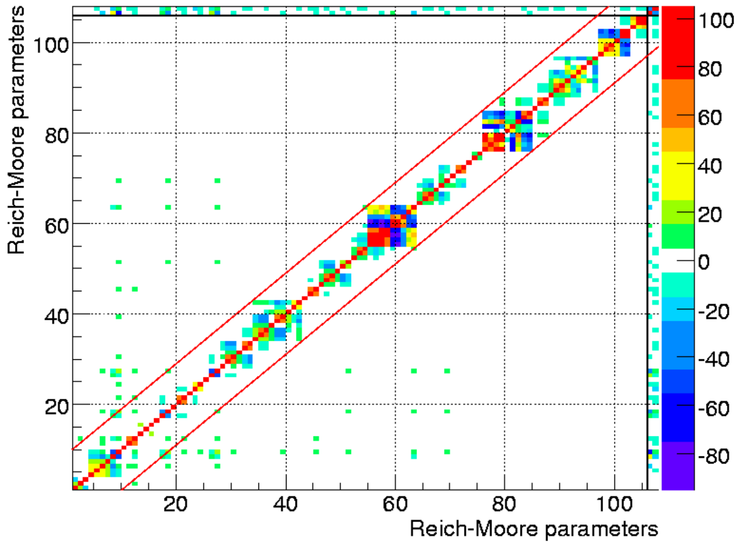
$^{237}Np(n,\gamma)$ measurement with the TAC

The n_TOF capture data have been analyzed in the RRR and URR together with the data of Gressier et al. (1999) from GELINA.

Capture (n_TOF) + Transmission (Gressier et al.) in the RRR



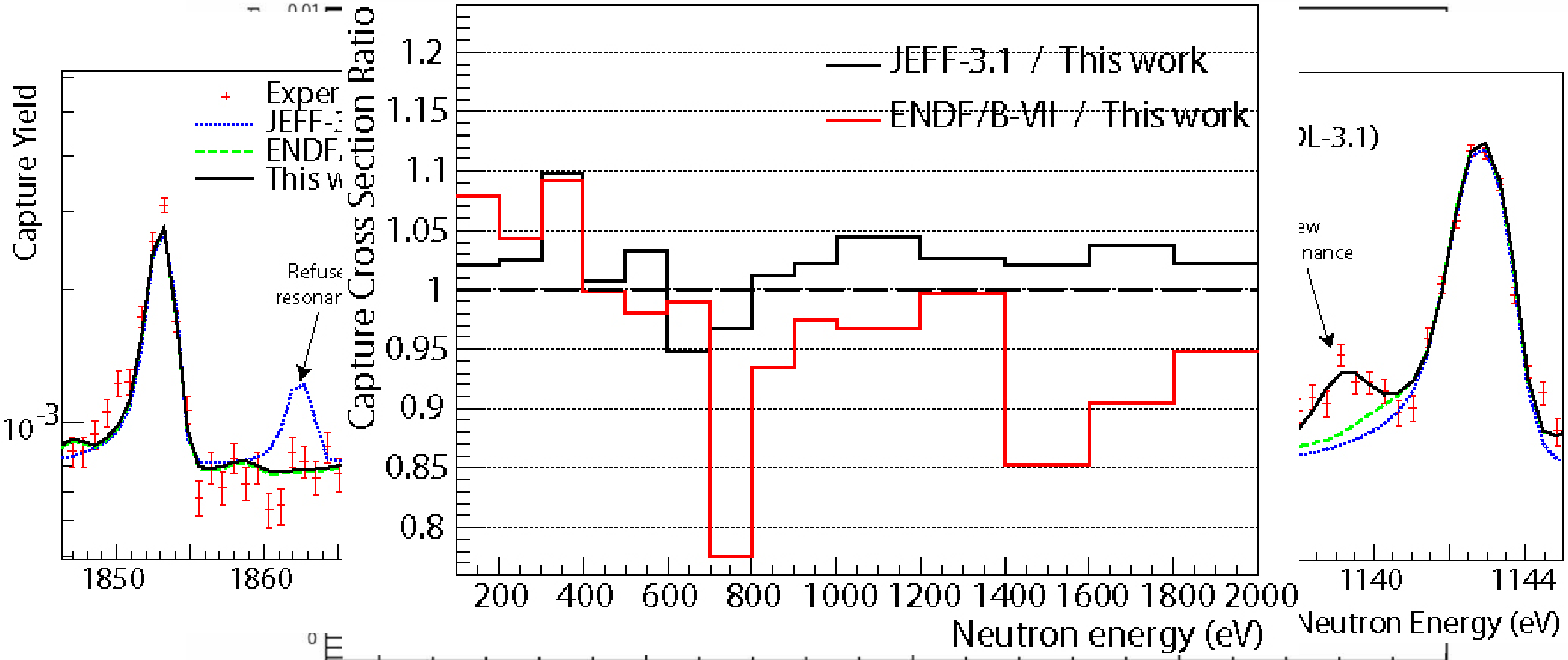
Res. Par. Cov. Matrix (incl. Norm. & back.)



Param.	FIT	CORRELATION		
		S_0	R'	$<\Gamma_\gamma>$
$S_0(10^{-4})$	1.04±0.06	1		
R' (fm)	9.4±0.5	0.8	1	
$<\Gamma_\gamma>$ (meV)	40.7±0.5	-0.4	-0.3	1
D_0 (eV)	0.56	-	-	-

^{240}Pu(n,γ) measurement with the TAC

The n_TOF capture data have been analyzed together with the data of W. Kolar et al. (1968) from GELINA. (Analysis above 110 eV, below data affected by inhomogeneity of the sample)



Among the 39 resonances proposed in the latest evaluation by Bouland et al.:

- 18 confirmed
- 14 refused
- 7 neither of both

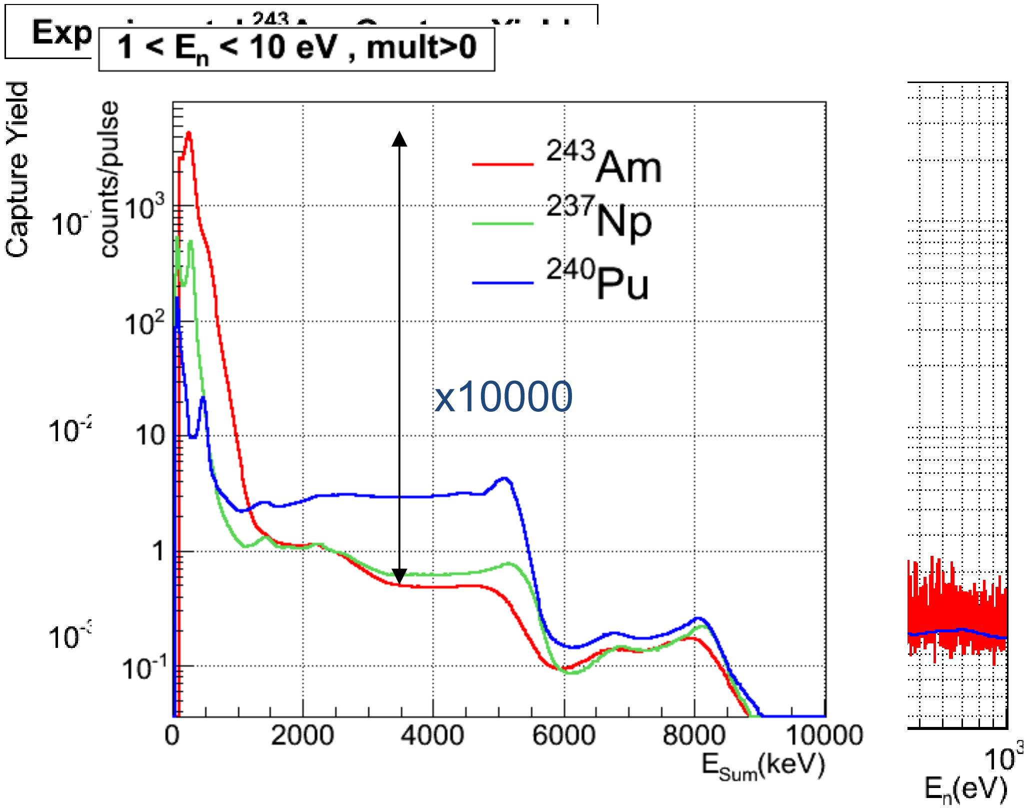
In addition, a total of 6 resonances have been observed for the first time.

$S_0(10^{-4})$	1.13	**1.04±0.08**	1.07

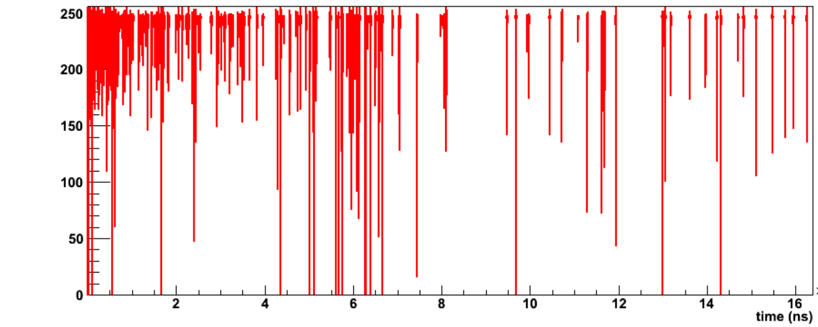
^{243}Am(n,γ) measurement with the TAC

The high activity (and high energy) of the intrinsic activity of the ^{243}Am sample caused problems due to:

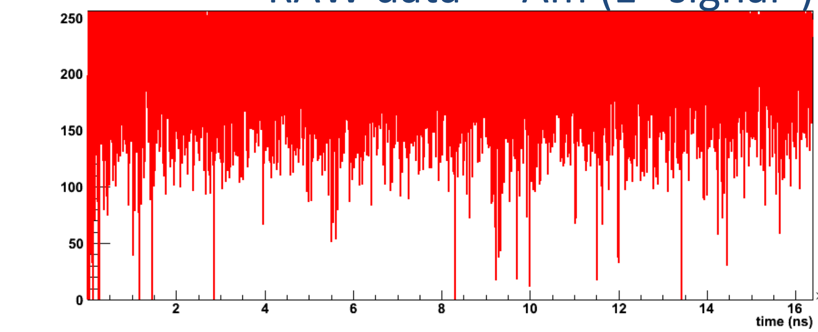
- High counting rate in the DAQ → summing of consecutive signals



Run 7896 BAF2_02 Event 1 RAW data ^{197}Au (102 "signals")



Run 7492 BAF2_02 Event 2 RAW data ^{243}Am (1 "signal")

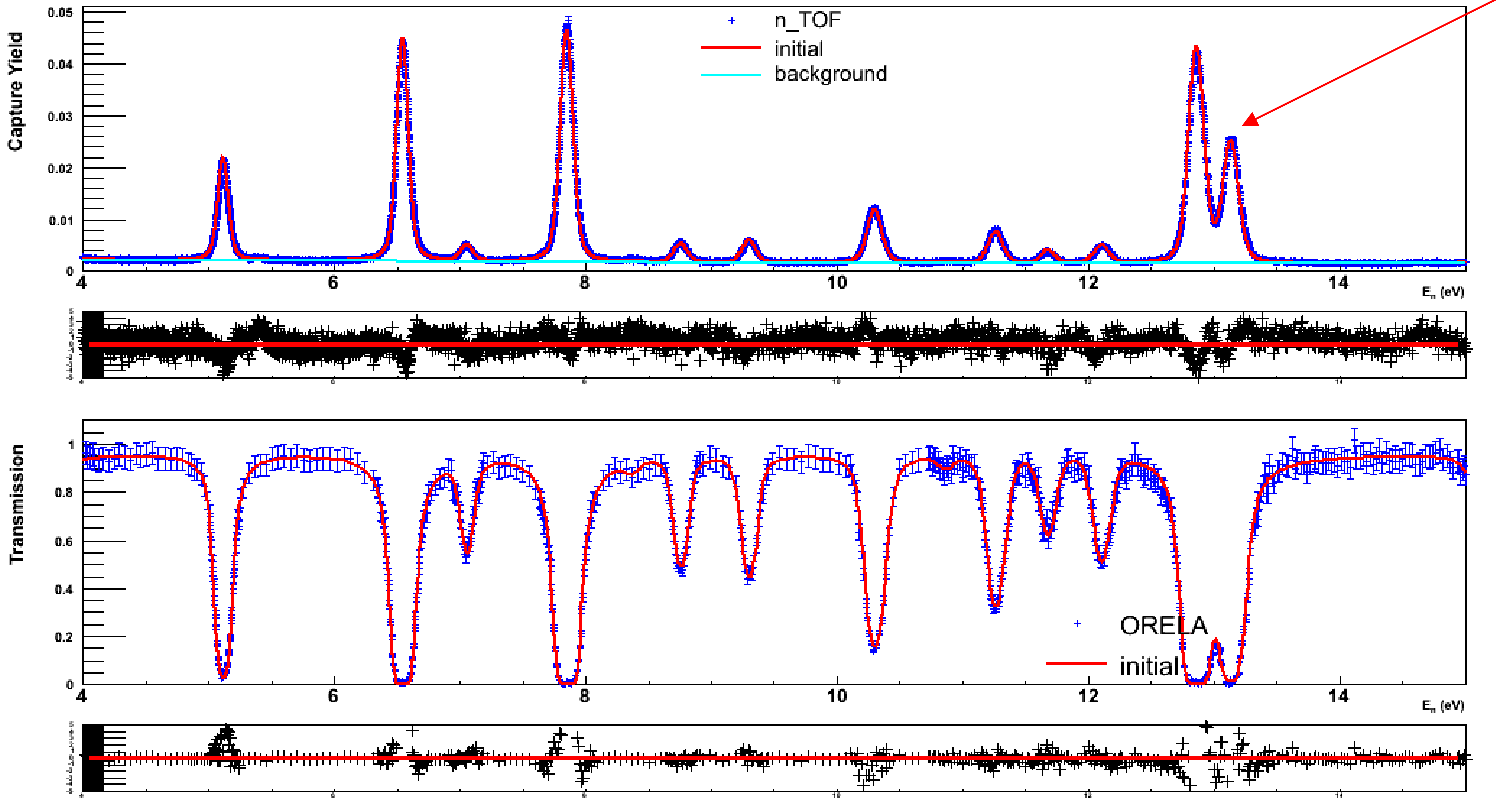


After validating the signal analysis routine in extreme case, we have obtained the capture yield with nice capture to background ratio.

^{243}Am(n,γ) measurement with the TAC

The n_TOF capture data have been analyzed normalized to the data of Simpson et al. (1974) from ORELA.

ENDF-VII.0 resonance parameters (not adjusted)



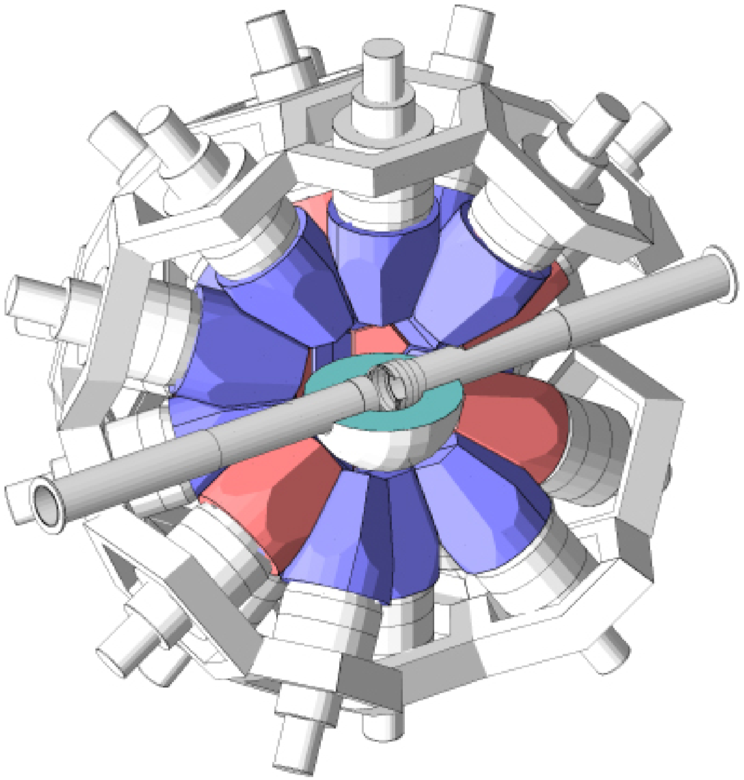
Good agreement at low energies → normalization

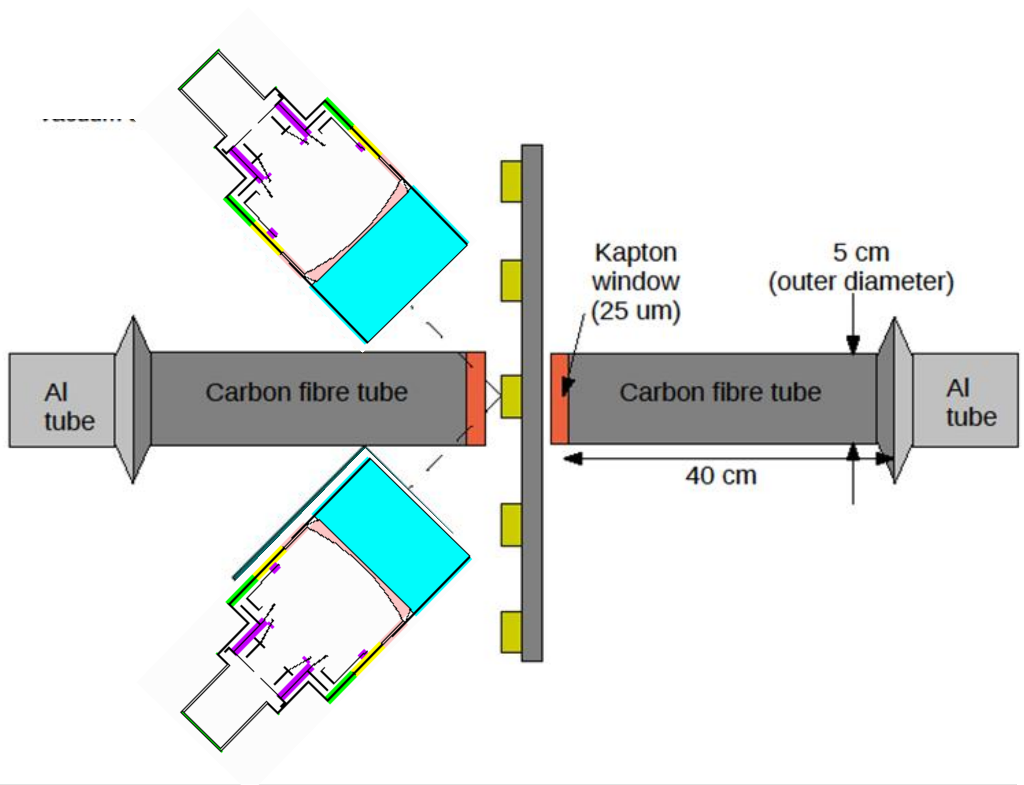
Better resolution/statistics at higher energies → improvement of the ^{243}Am cross section

Campaign 2010: ^{241}Am(n,γ) measurement with the TAC and C6D6

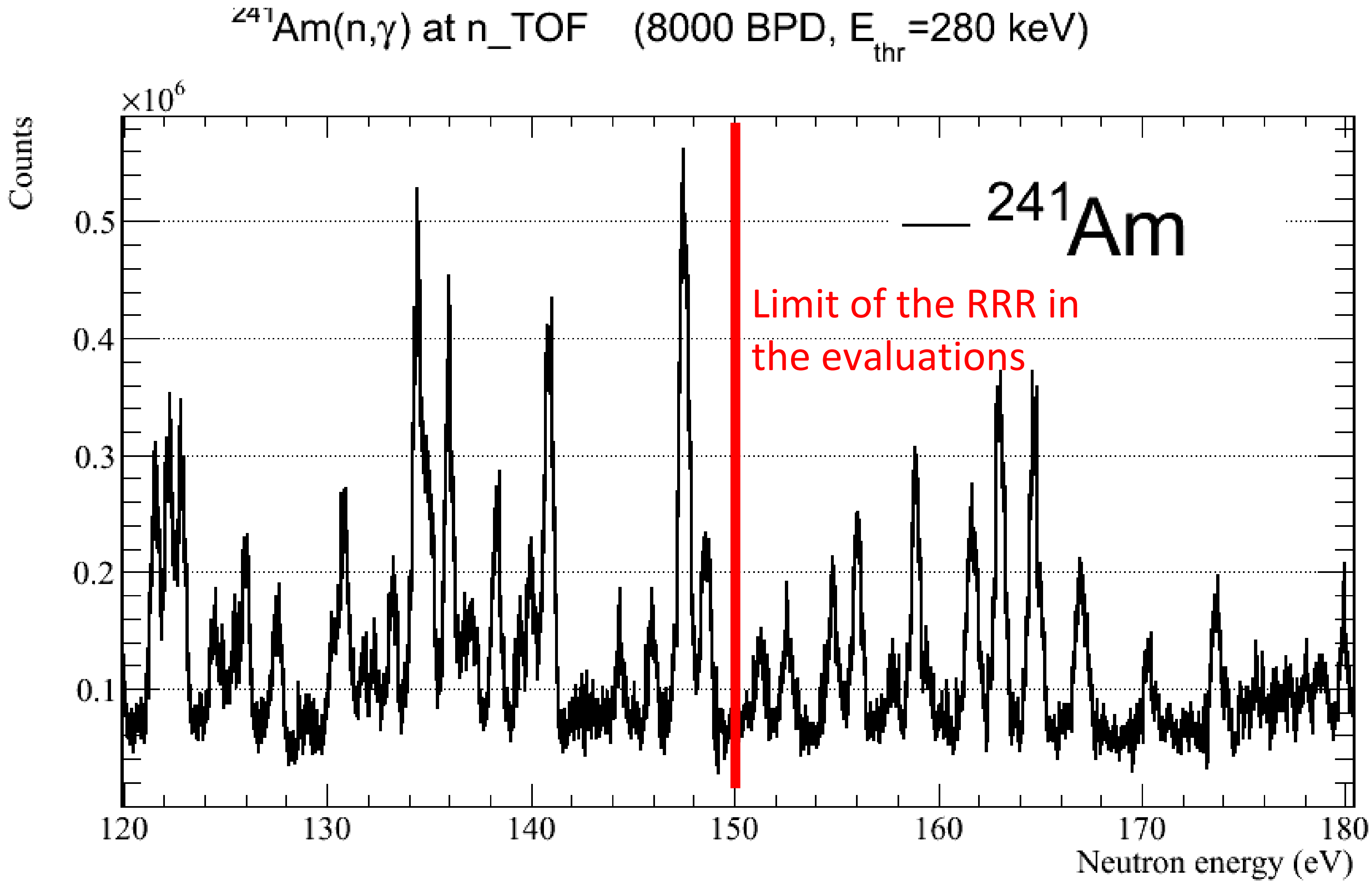
This measurement, as well as the planned ^{238}U, will be performed combining for the first time the TAC and C6D6:

1. Reduction of systematic errors
2. Study of the complete range between thermal and 1 MeV (already achieved for ^{232}Th)
3. Extension of the RRR thanks to high statistics of the TAC

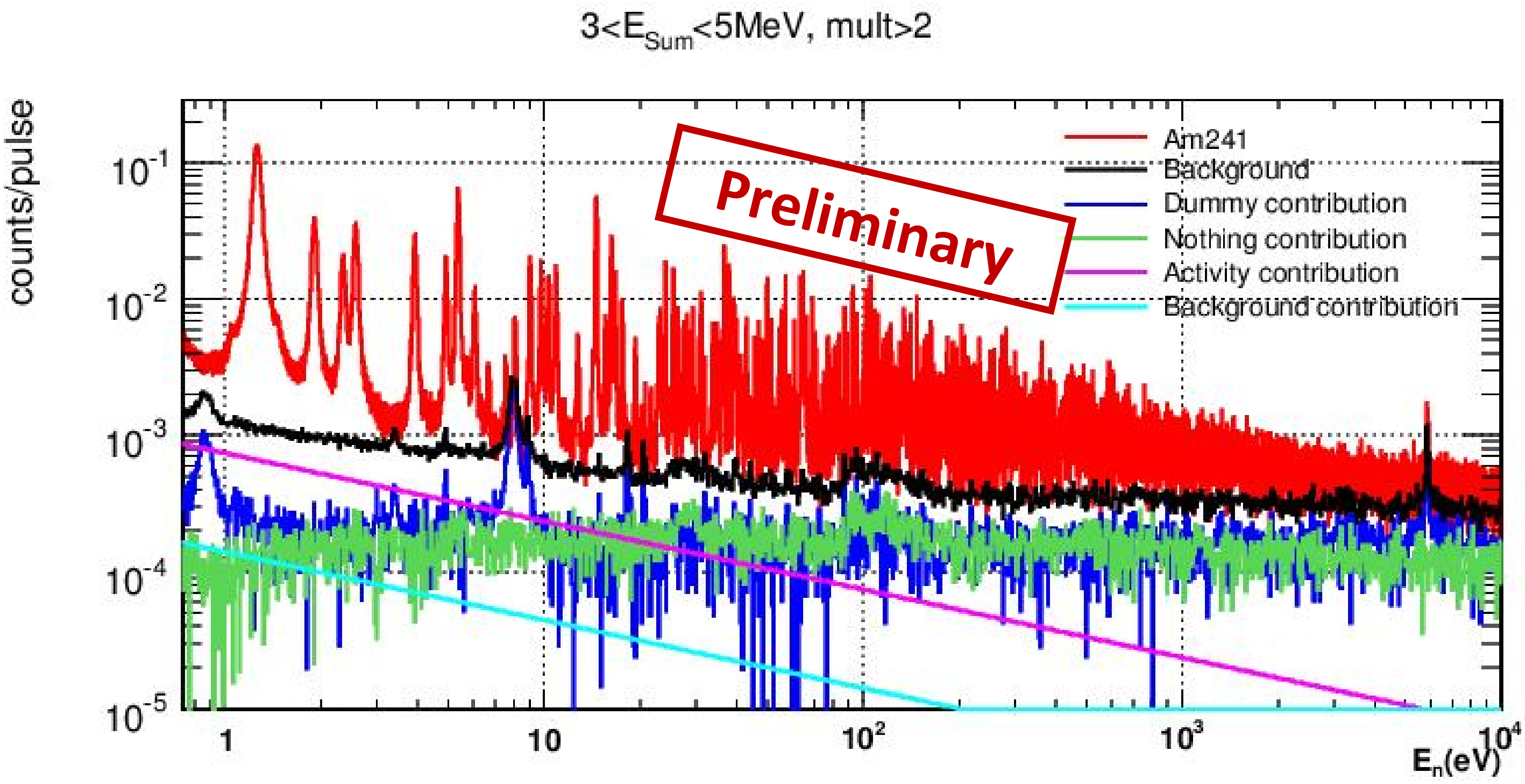




Campaign 2010: $^{241}Am(n,\gamma)$ measurement with the TAC and **C6D6**

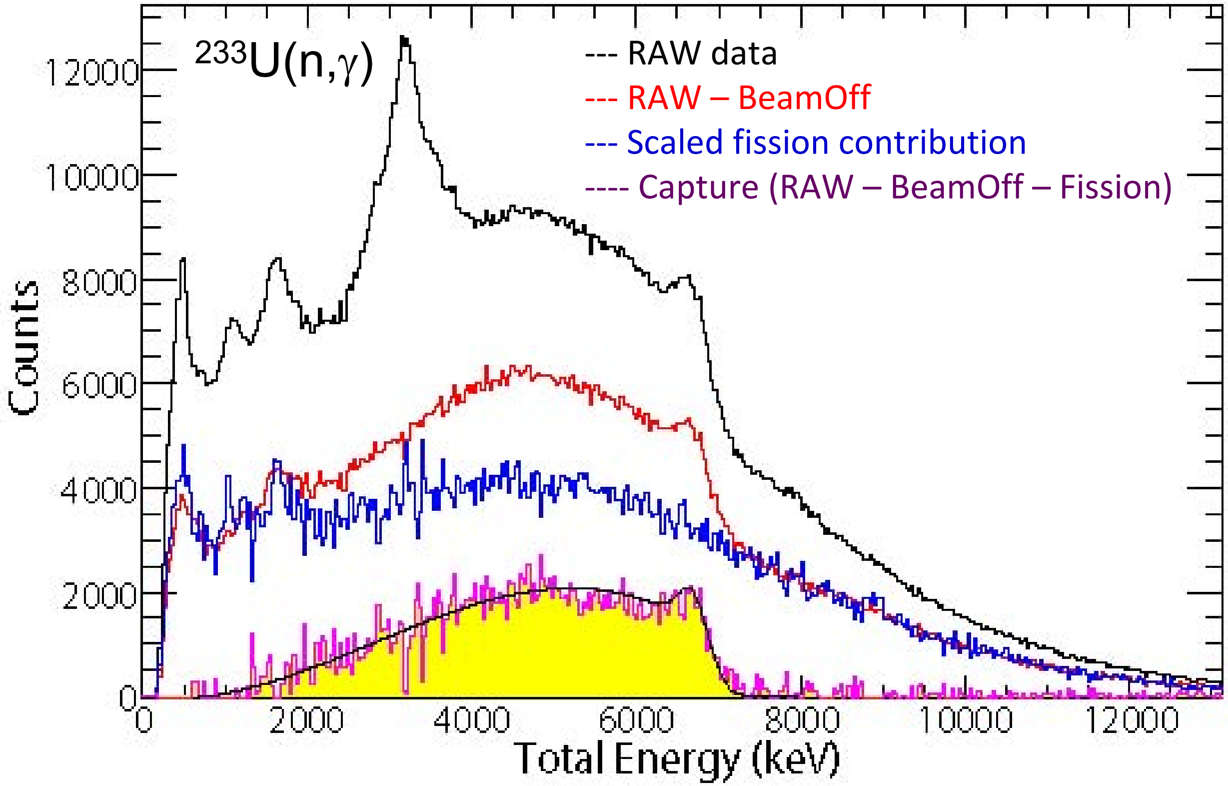


Campaign 2010: ^{241}Am(n,γ) measurement with the **TAC** and C6D6



Campaign 2010: Simultaneous (n,γ)+(n,f) measurements

Measurements on capture cross sections of fissile isotopes are difficult due to the large background from fission reactions.

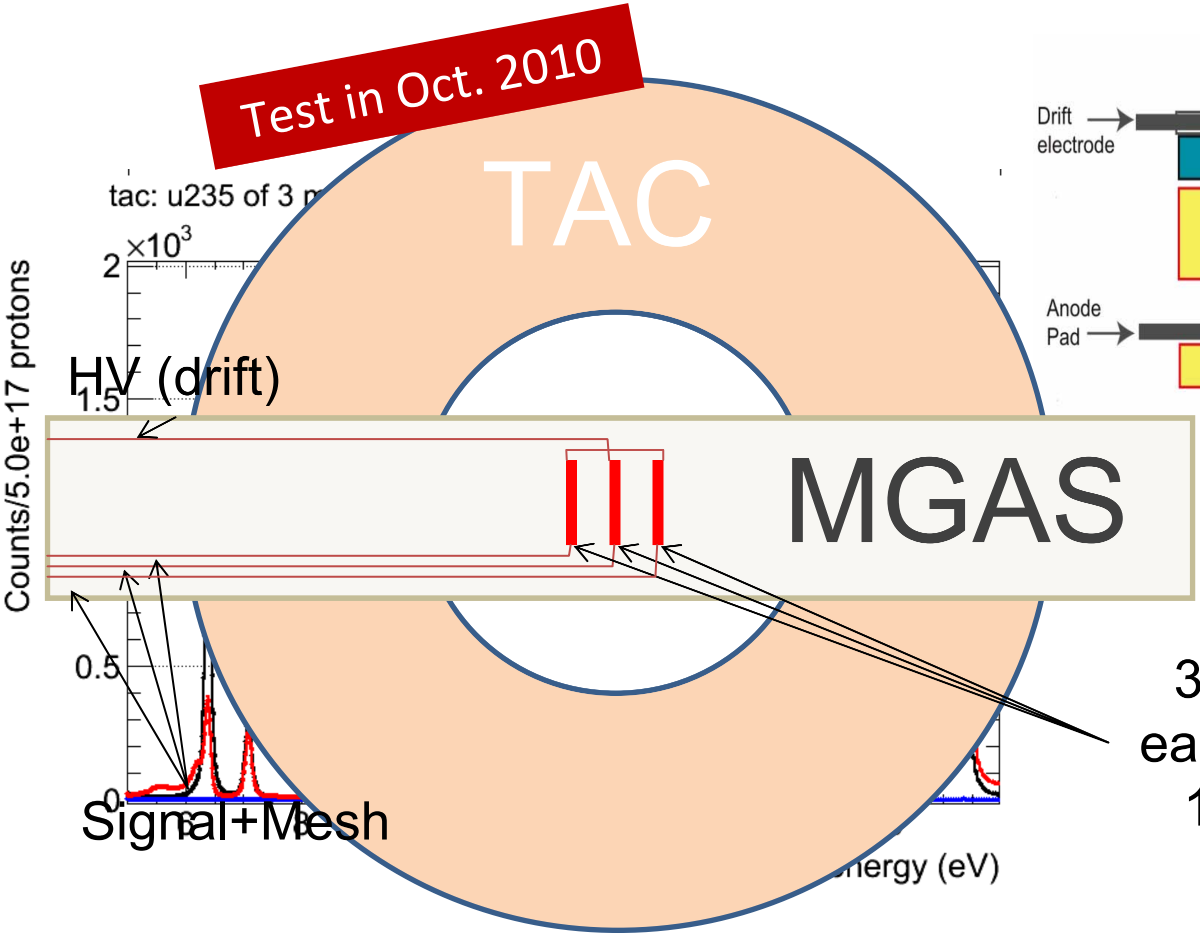


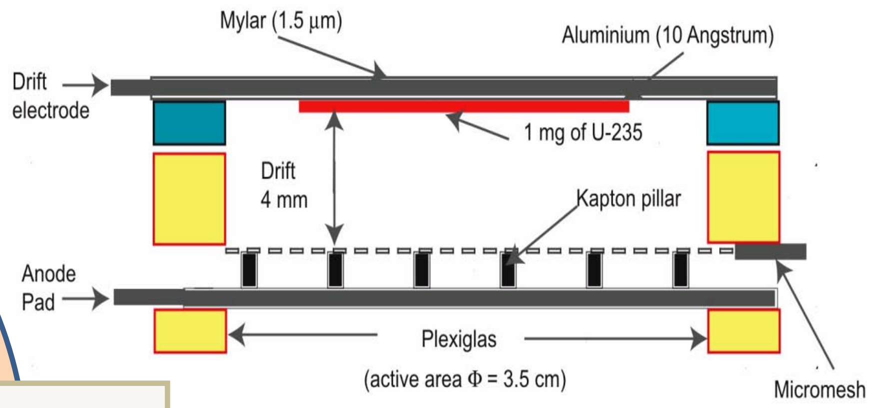
The analysis is possible thanks to the excellent capabilities of the TAC, but the accuracy is limited to ~10-15%.

Campaign 2010: Simultaneous (n,γ)+(n,f) measurements

The test experimental set-up combines the use of the TAC (for capture) with a total of three MGAS (for fission) detectors loaded with ^{235}U samples.

MGAS: excellent performance in 2009 + VERY TRANSPARENT





3 MGAS detectors each equipped with a 1 mg ^{233}U sample

Summary

The research carried out at the CIEMAT Nuclear Innovation Unit covers the wide range of fields associated to the design of Advance Nuclear Reactors:

micro and macroscopic experiments as well as design studied of advanced fuel cycles and Gen-IV reactors.

The research line on Basic Nuclear Data is specialized in measurements of

- neutron induced cross section measurements and
- neutron delayed emission, as well as in the
- simulation of γ-ray and neutron detectors.

The Nuclear Innovation Unit takes full advantage of the combination of the n_TOF facility at CERN with the Total Absorption Calorimeter TAC for measuring accurate neutron capture cross sections of actinides:

-^{233,234}U, ^{237}Np, ^{240}Pu and ^{243}Am have been already measured and analyzed

-^{241}Am is ongoing, to be combined with C6D6 data (very promising preliminary results)

-Simultaneous (n,γ)(n,f) on ^{235}U to be tested in October 2010

-^{238}U to be measured in April 2011, again combining TAC and C6D6

CIEMAT will open one postdoc position in the near future to work in this field.

DIGITISER DESIGN (Colaboración con la Unidad de Electrónica del CIEMAT, J. Marín y J. Castilla)

- Two interlaced ADCs of 500 MS/s and 12 bit resolution, 1GHz bandwidth, 2Vpp.
- FPGA Virtex-4 (signal pre-processing)
- Fast DSP (pulse shape analysis)
- TDC (time signal determination)
- 2 Gb on board memory DDR
- Input ranges: 100, 200, 500 mV & 1,2 V
- External synchronization
- Fast data bus (not yet decided).
- Operation Mode: on line psa or fast transmission
- 30 units cost estimate: < 2000 € / channel