High accuracy measurement of the $^{238}U(n,\gamma)$ cross section with the TAC at the CERN n_TOF facility

T. Wright[1], C. Guerrero[2], D. Cano-Ott[3], E. Mendoza[3], J. Billowes[1], F. Mingrone[4], C. Massimi[4], F. Gunsing[5]

[1] School of Physics and Astronomy, University of Manchester (UK)

[2] CERN, Geneva (CH)

[3] CIEMAT, Nuclear Innovation Unit, Madrid (ES)

4. Dipartimento di Fisica e Astronomia – Universita di Bologna and Instituto Nazionale di Fisica Nucleare (IT)

5. CEA, Saclay (FR)

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Outline

- Motivation and Objectives
- The Experiment
- Data Analysis: raw data to capture yield
  - TOF to En calibration
  - Analysis conditions in E_{sum} and m_{cr}
  - Background subtraction
  - Dead-time and pile-up correction
  - Summary of uncertainties
- Results

Motivation and Objectives

Features on the NEA high priority request list

Requested uncertainties:
- 0.01 -1 keV: **1%** **(2%)**
- 1-10keV: **1%** **(3%)**
- 10-25keV **3%** **(9%)**

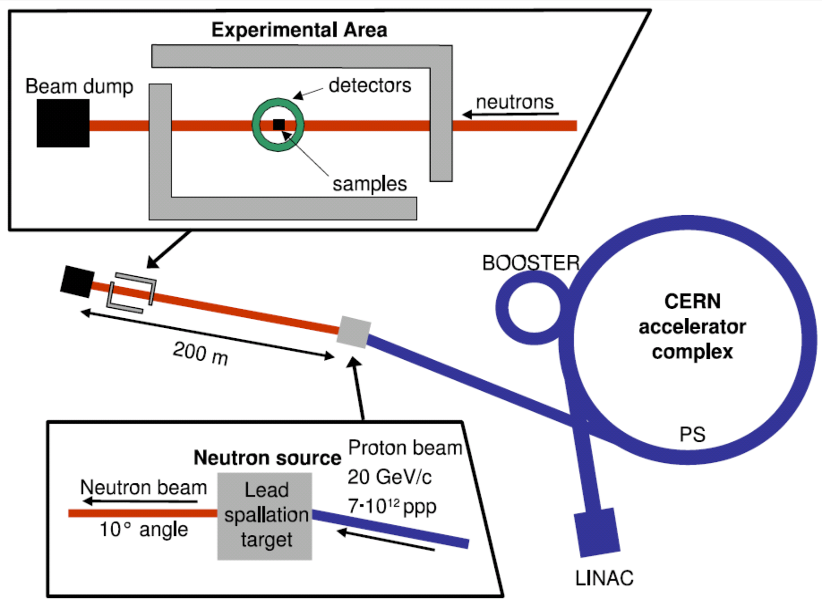
“The objective of the present work is thus to obtain a capture yield, the observable in capture cross section measurements, with a statistical uncertainty lower than 2% and a similar systematic uncertainty in the full energy range between 1 eV and 25 keV.

Three separate measurements will meet this objective:

1. **Total absorption calorimeter, n_TOF**
2. **C_6D_6 detectors, n_TOF (Contact F. Gunsing)**
3. **C_6D_6 detectors, GELINA**

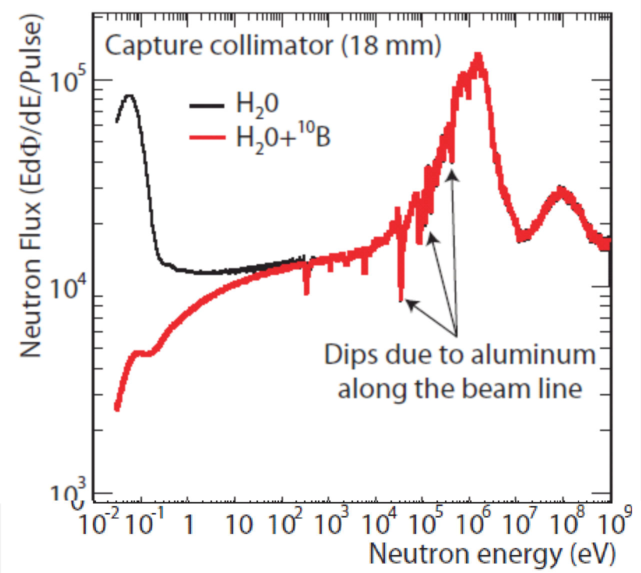
The n_TOF facility

The n_TOF facility is a high instantaneous intensity spallation neutron source driven by the CERN PS synchrotron (20 GeV/c with 7×10^{12} ppp)



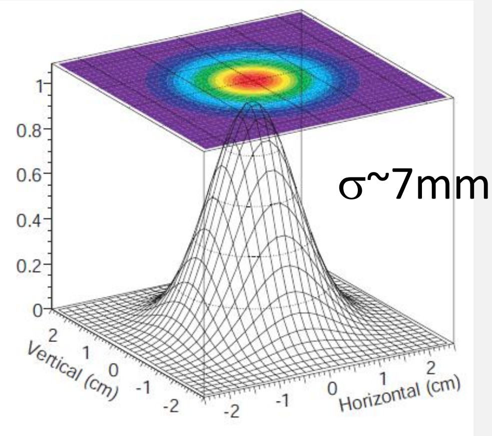
C. Guerrero et al., Eur Phys. J. A 49:27 (2013)

Main characteristics of the n_TOF facility

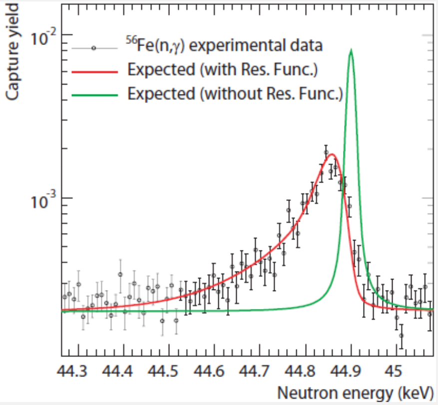


$0.6\cdot10^{6}$ neutrons/pulse (capture mode)

$12\cdot10^{6}$ neutrons/pulse (fission mode)



σ~7mm



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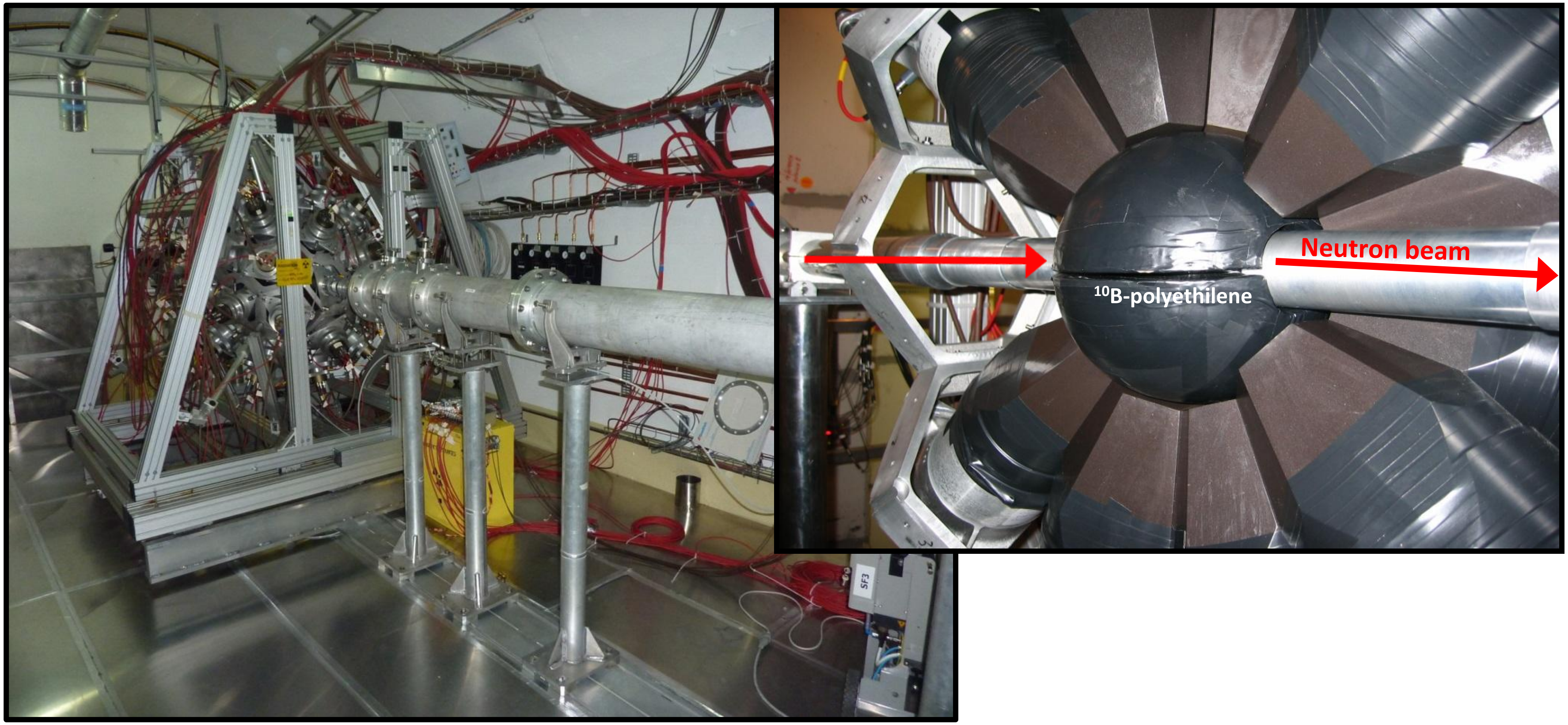
TOF

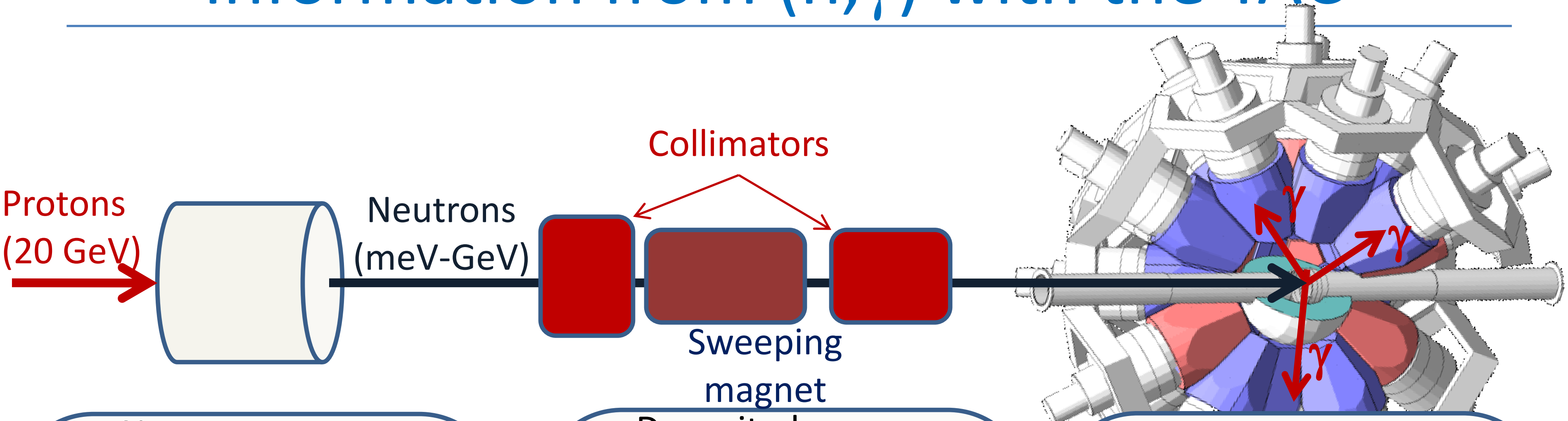
The TAC

The n_TOF Total Absorption Calorimeter (TAC)

- High-efficiency **4π** detector (40 BaF_2 scintillators with neutron absorber)
- Digital acquisition system (40 digitizers with 8 bits sampling at 250 MHz)
- Background discrimination by energy and multiplicity



Information from (n,γ) with the TAC



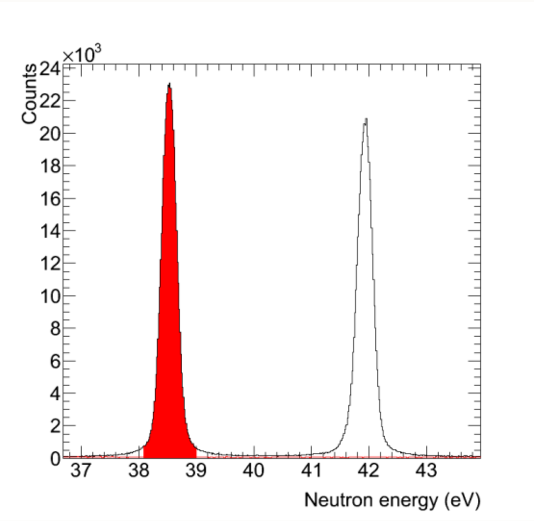
Protons (20 GeV)

Neutrons (meV-GeV)

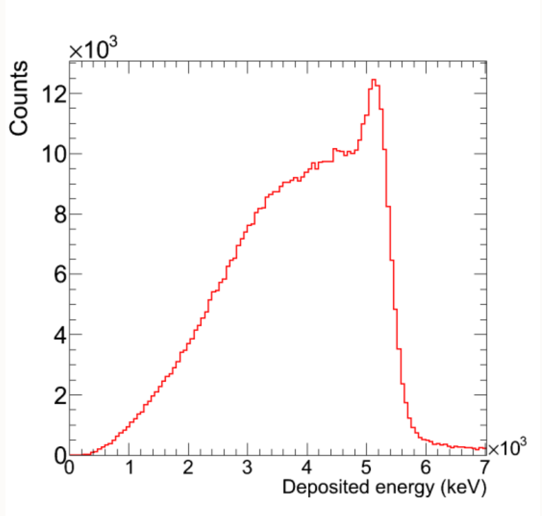
Collimators

Sweeping magnet

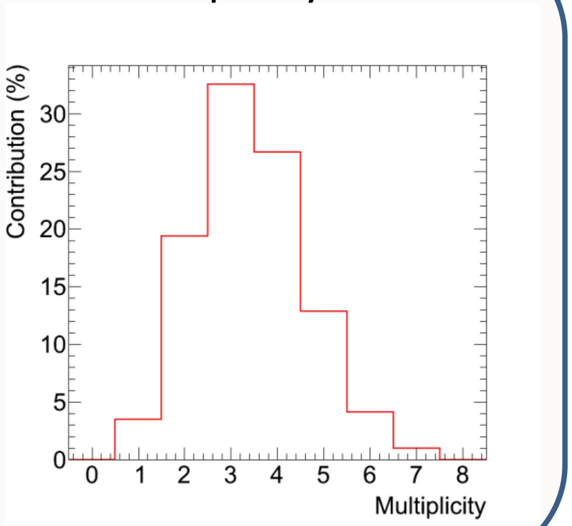
Neutron energy



Deposited energy



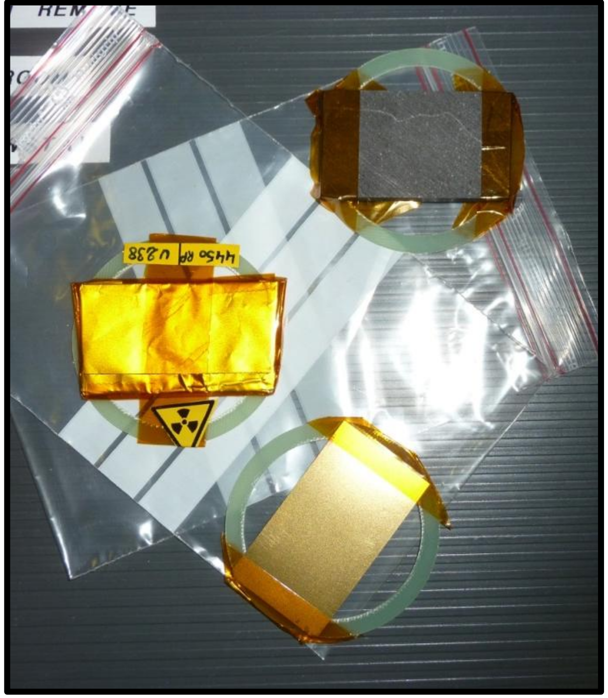
Multiplicity



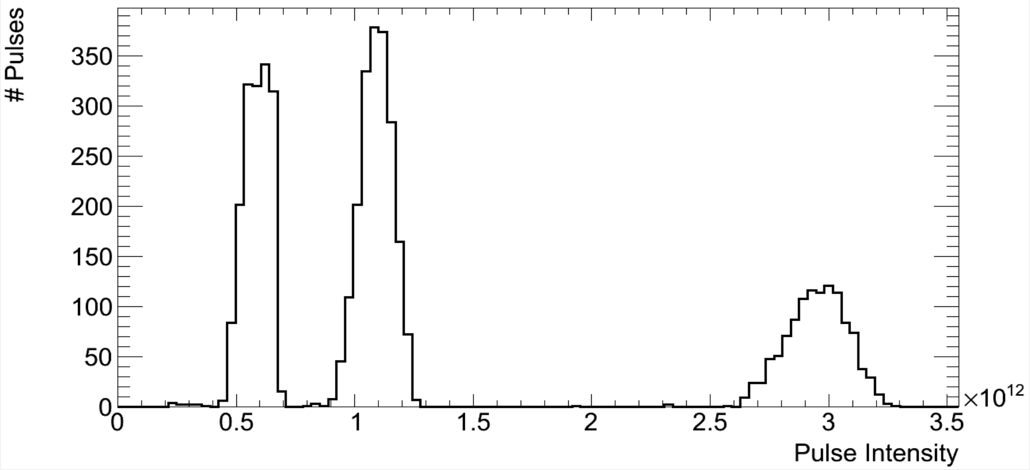
The measurement

Sample	Size (mm)	Mass (g)	Protons	Time
^{238}U	52.80x30.02	6.125±0.002	4.12e+17	24d 16:15:02 ~ 60%
Nothing (sample out)	-		1.05e+17	6d 16:56:14 ~ 16%
Gold	53.3x30.0	1.547	6.74e+16	6d 10:30:54 ~ 16%
Carbon	53.35x30.65	14.638	7.05e+16	2d 17:49:28 ~ 7%

^{238}U sample from JRC-IRMM



The TAC suffers pile-up signals for high counting rates (τ_{slow}=630 ns); thus given the mass of the ^{238}U and the high accuracy aimed for, most of the measurements have been carried out at very low intensity (8% of nominal) and also other values in order to validate the pile-up and dead-time corrections applied.

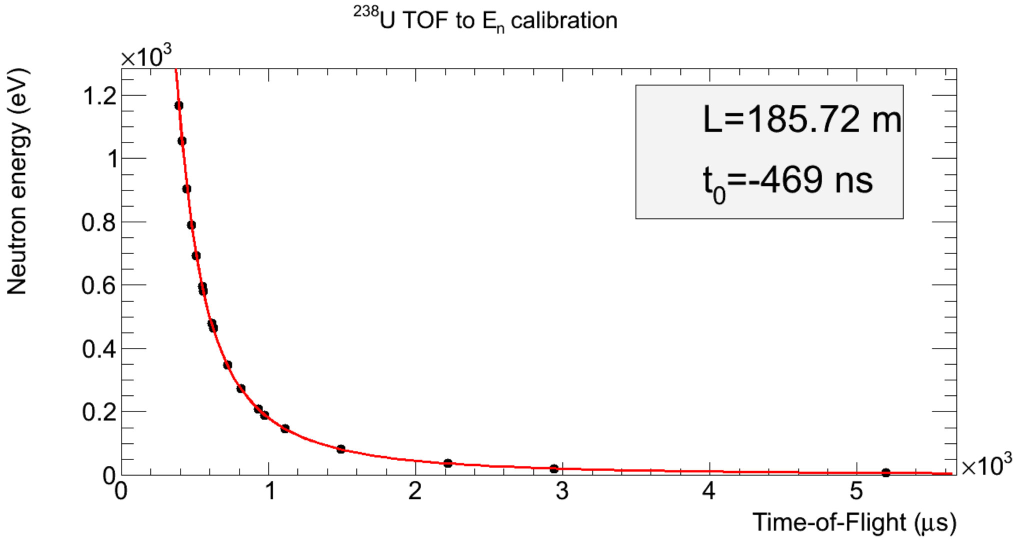


Analysis: ToF to E_n calibration

$$E_n\,(eV) = \left(\frac{72.2983\cdot L(m)}{t_{tof}(\mu s) - tpkup(\mu s) - t_0(\mu s)}\right)^2$$

Taking the PKUP signal as start time, the ToF/E_n calibration (L and t_0) has ben performed with reference to the following ^{238}U resonances.

Resonance energy (eV)	TOF (μs)		Resonance energy (eV)	TOF (μs)
6.673	5197.98		463.328	623.325
20.864	2939.35		478.524	613.365
36.671	2217.10		580.238	556.949
80.75	1493.72		595.21	549.914
145.673	1112.25		693.25	509.502
189.8	974.148		791.03	476.949
208.537	929.398		905.3	445.788
273.7	811.170		1054.87	412.949
347.855	719.478		1168.12	392.411



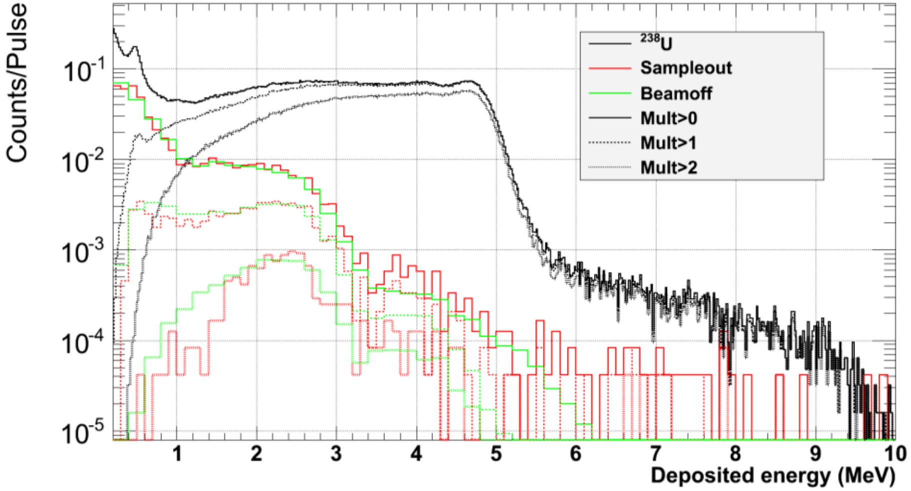
Analysis: condition in m_{cr} and E_{sum}

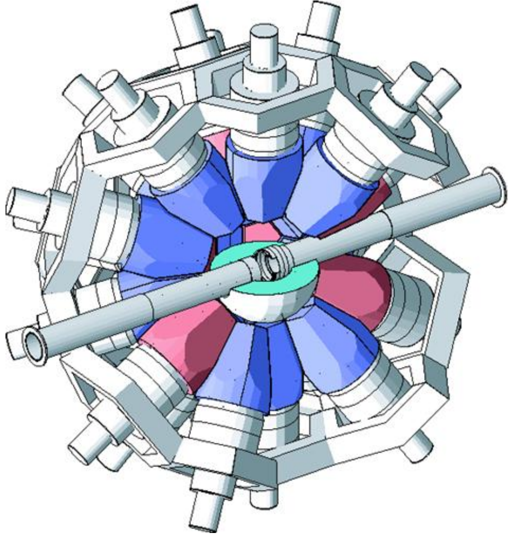
The TAC allows maximizing the signal to background ratio by setting conditions in m_{cr} and E_{sum}. These conditions affect as well the:

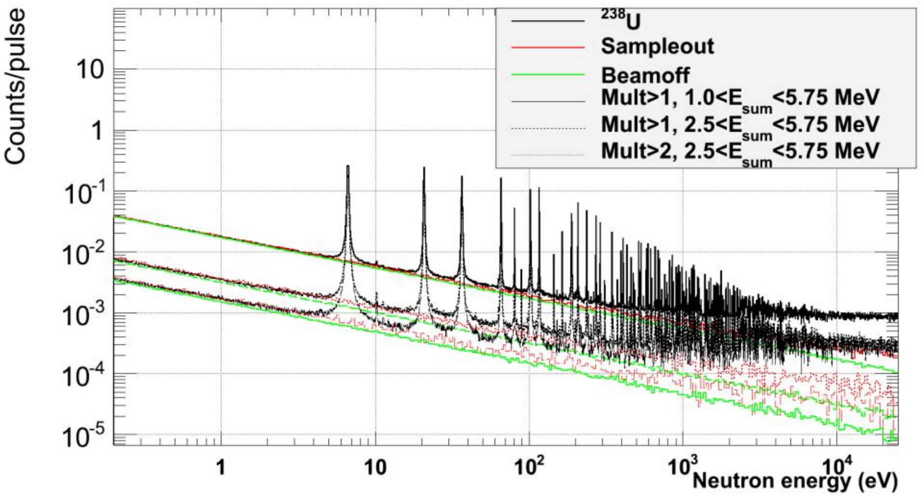
- Detection efficiency
- Pile-up losses
- Neutron sensitivity

We have chosen: **$m_{cr}>1$ and $2.5<E_{sum}$(MeV)<5.75**

- Eliminates 478 keV γ-rays from $^{10}B(n,\alpha\gamma)$
- Eliminates 2.2 MeV γ-rays from $^{1}H(n,g)$
- Eliminates high energy background (above ^{238}U S_n)
- Eliminates low multiplicity background ($m_{cr}=1$)
- Allows keeping a large fraction of the statistics

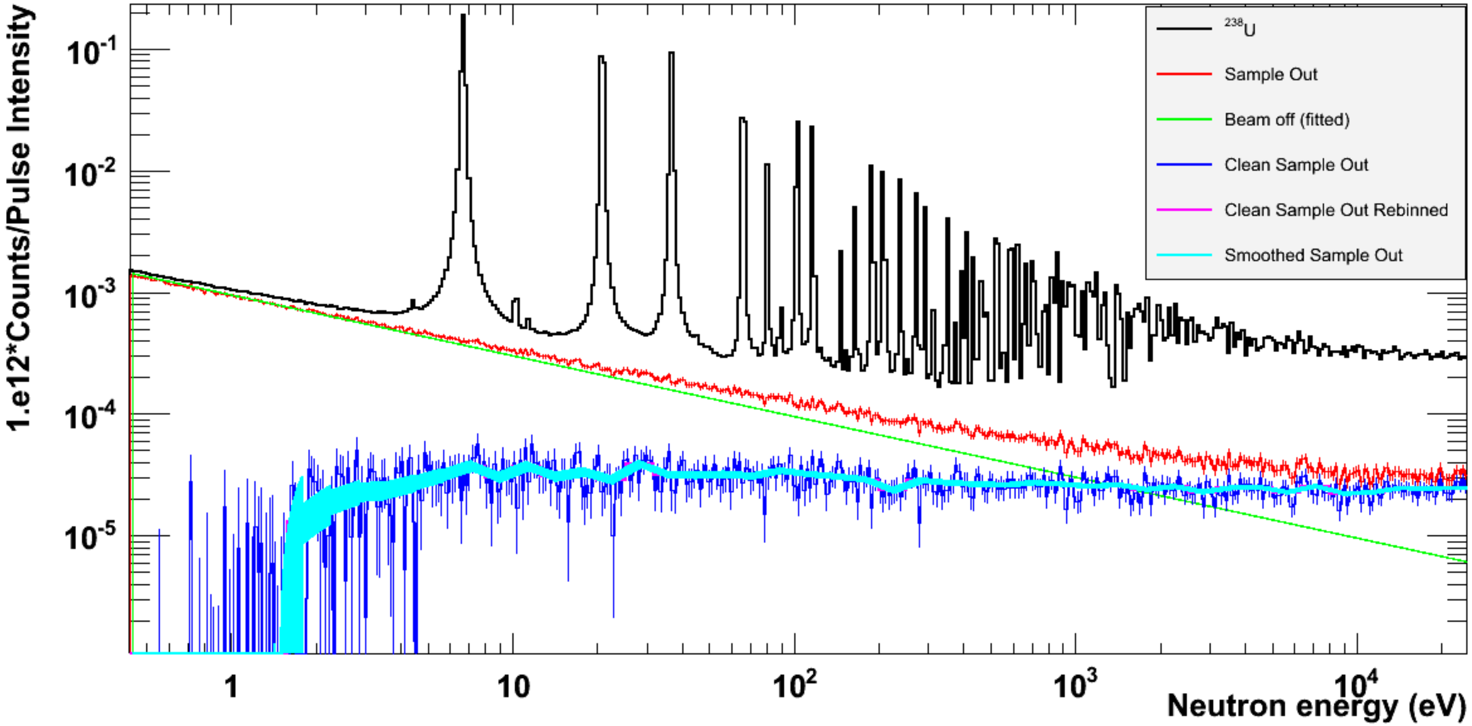






Analysis: Background subtraction (I)

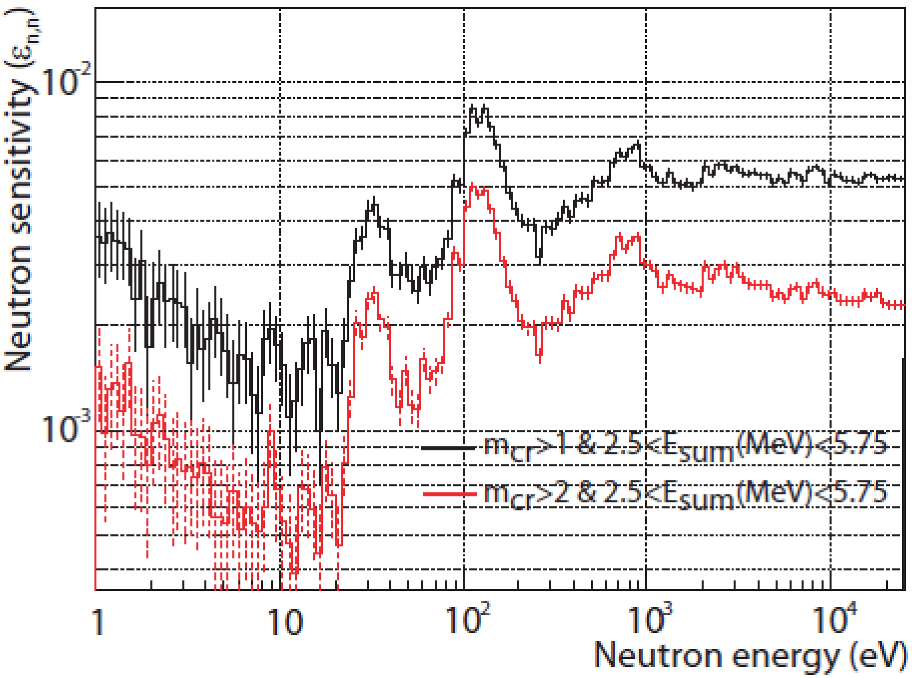
- Beam off background fitted using a linear function on a log-log scale
- Sample out background re-binned & smoothed, then interpolating adjacent bins.
- No sample canning so the background contribution remains below 15%
- Above ~10 keV we will be unable to analyse due to the γ-flash
- Neutron scattering background (see next slide)



Analysis: neutron scattering background

The neutron sensitivity, $\varepsilon_{n,n}$ is defined as the probability of detecting a neutron. This is found experimentally for the TAC by measuring a carbon sample, which can be considered a pure neutron scatterer.

By comparing the measured experimental yield with the theoretical yield, the neutron sensitivity is found from the scaling factor.



$$Y(E_n)^{obs}_{n,n} = \frac{C(E_n) - B(E_n)}{N(E_n).\varepsilon.\varphi_n(E_n)} \longrightarrow Y(E_n)^{th}_{n,n} \approx 1 - e^{\sigma x}$$

$C(E_n)$ = Counts $B(E_n)$ = Background counts

$N(E_n)$ = Beam interception factor

ε = Efficiency $\varphi_n(E_n)$ = Neutron Flux

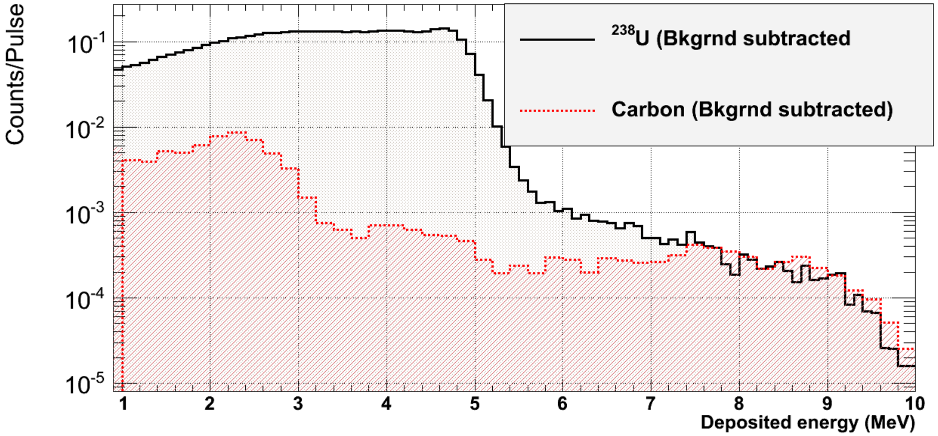
σ = Cross section x = Thickness

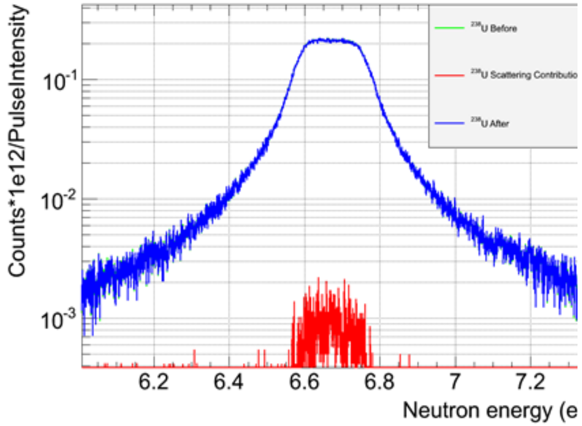
The neutron sensitivity changes with neutron energy due to resonances in the barium isotopes. Furthermore, it is reduced by stricter conditions on neutron multiplicity. The use of a borated polyethylene neutron absorber vastly reduces the scattering background.

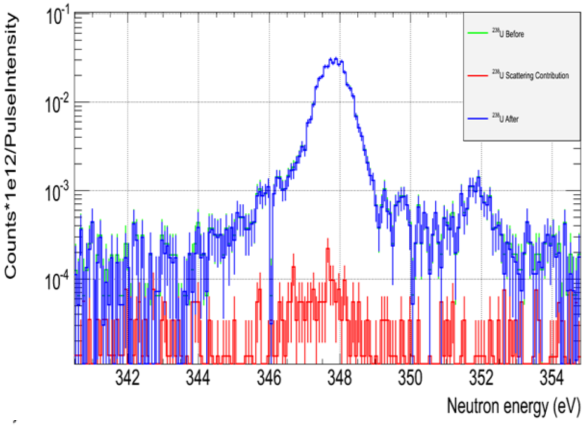
Analysis: Background subtraction (II)

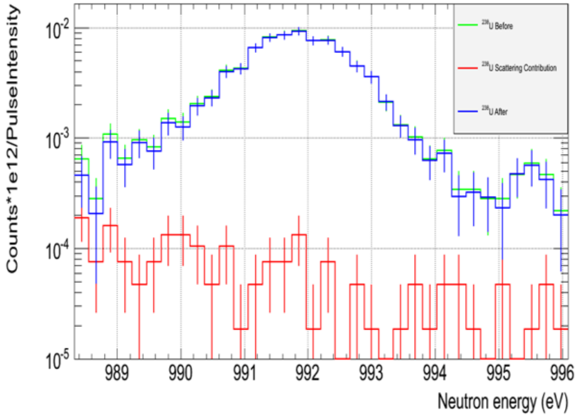
The $^{238}U_{n,n}$ backg. is calculated by comparing the high energy (E_{sum}>7 MeV) TAC response to ^{238}U and ^{nat}C

Although the neutron sensitivity of the TAC is ~0.4%, the background from $^{238}U(n,n)$ is smaller in the keV region is much smaller than $\frac{\varepsilon_{n,n}\sigma_{n,n}}{\varepsilon_{n,g}\sigma_{n,g}}$ because the time that a neutron needs to transverse the TAC (~500 ns for 1 keV) is longer than the width of the resonance (~400 ns at 1 keV, 100 ns at 5 keV)







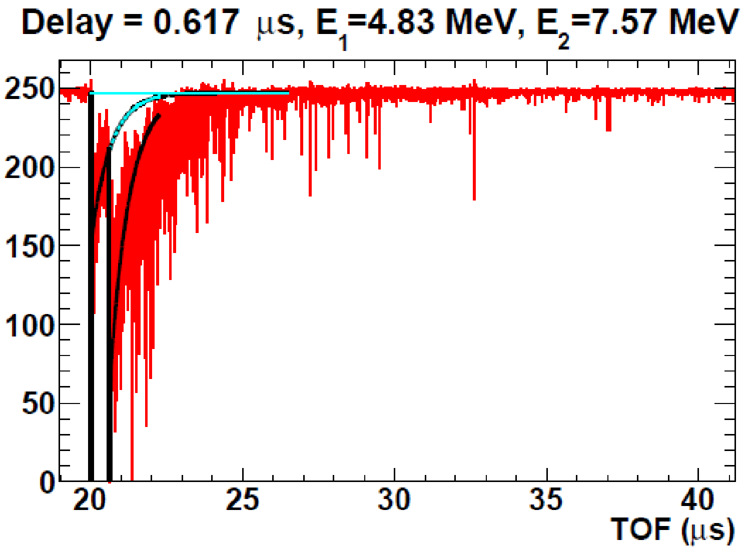


A preliminary comparison with the data from n_TOF C_6D_6 detectors, which do not suffer from neutron sensitivity problems, shows that even for resonances largely dominated by scattering (102 eV with $\sigma_{n,n}/\sigma_{n,g}$~3 and 2186 eV with $\sigma_{n,n}/\sigma_{n,g}$~30) are in good agreement between the TAC and the C_6D_6.

Chapter 3. Analysis: Dead-Time and Pile-Up

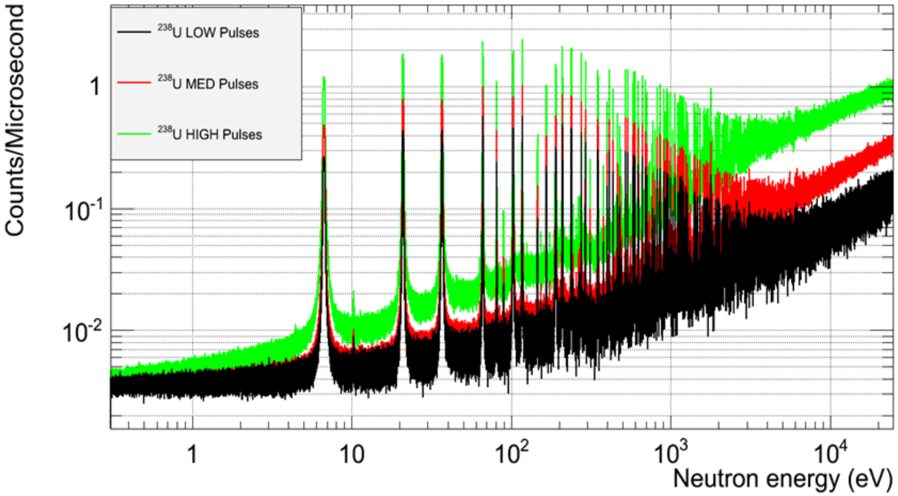
The problem:

The slow component of BaF2 has t_{slow}=630 ns and thus it becomes complicated to identify consecutive signals (within few μs).



Minimising the problem:

The n_TOF beam intensity was reduced in order to reduce the count rate. Furthermore, three different beam intensities were used to give three different count rates, facilitating a validation of the pile up correction.



Chapter 3. Analysis: Dead-Time and Pile-Up

Solving the problem:

A Monte Carlo simulation method that mimics the full counting and coincidence process in the TAC. Taking as input:

1) the measured counting rate distribution,

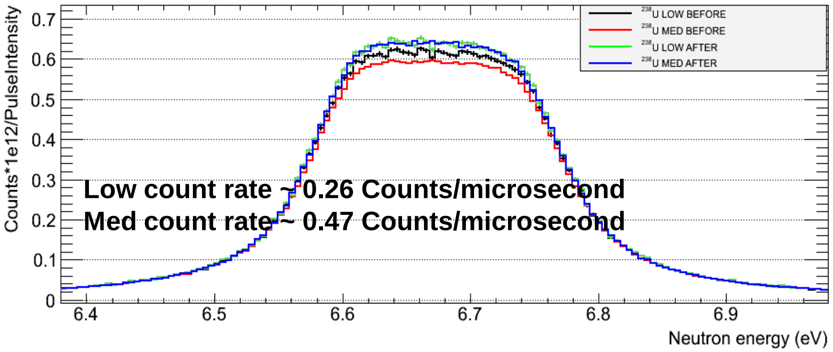
2) (n,γ) cascades in list mode from low counting rate

3) the identification probability for consecutive signals as function of the energy and time distance.

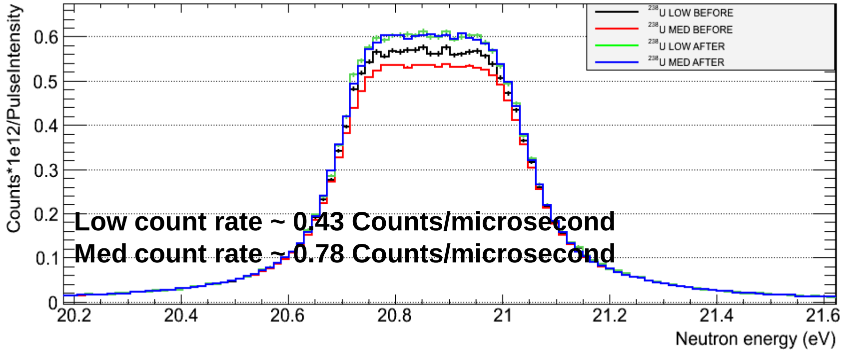
The program determines weather each signal survives or is killed by a previous one and then calculates the overall size of the dead-time losses and its effect on the detection efficiency for any analysis conditions on deposited energy and crystal multiplicity.

The full details of this innovative dead-time correction method are given in:

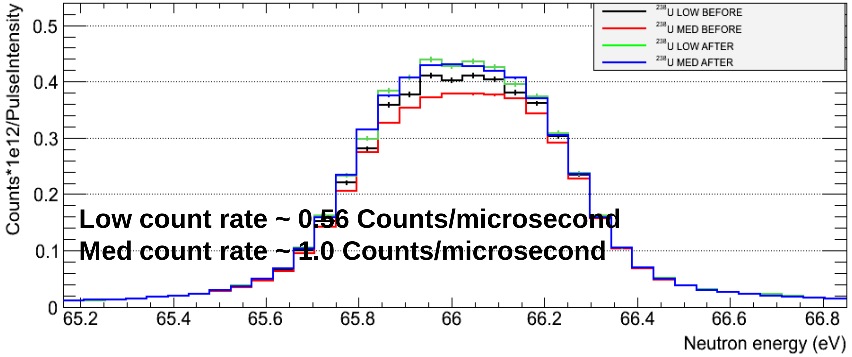
- E. Mendoza et al., “Pulse pile-up and dead time correction methods applied to the digitized signals of a segmented BaF2 Total Absorption Calorimeter used in (n,g) cross section measurements”, in preparation.
- C. Guerrero et al., “A Monte Carlo based pile-up and dead-time correction method for measurements in coincidence with detector arrays”, in preparation.



Low count rate ~ 0.26 Counts/microsecond
Med count rate ~ 0.47 Counts/microsecond



Low count rate ~ 0.43 Counts/microsecond
Med count rate ~ 0.78 Counts/microsecond



Low count rate ~ 0.56 Counts/microsecond
Med count rate ~ 1.0 Counts/microsecond

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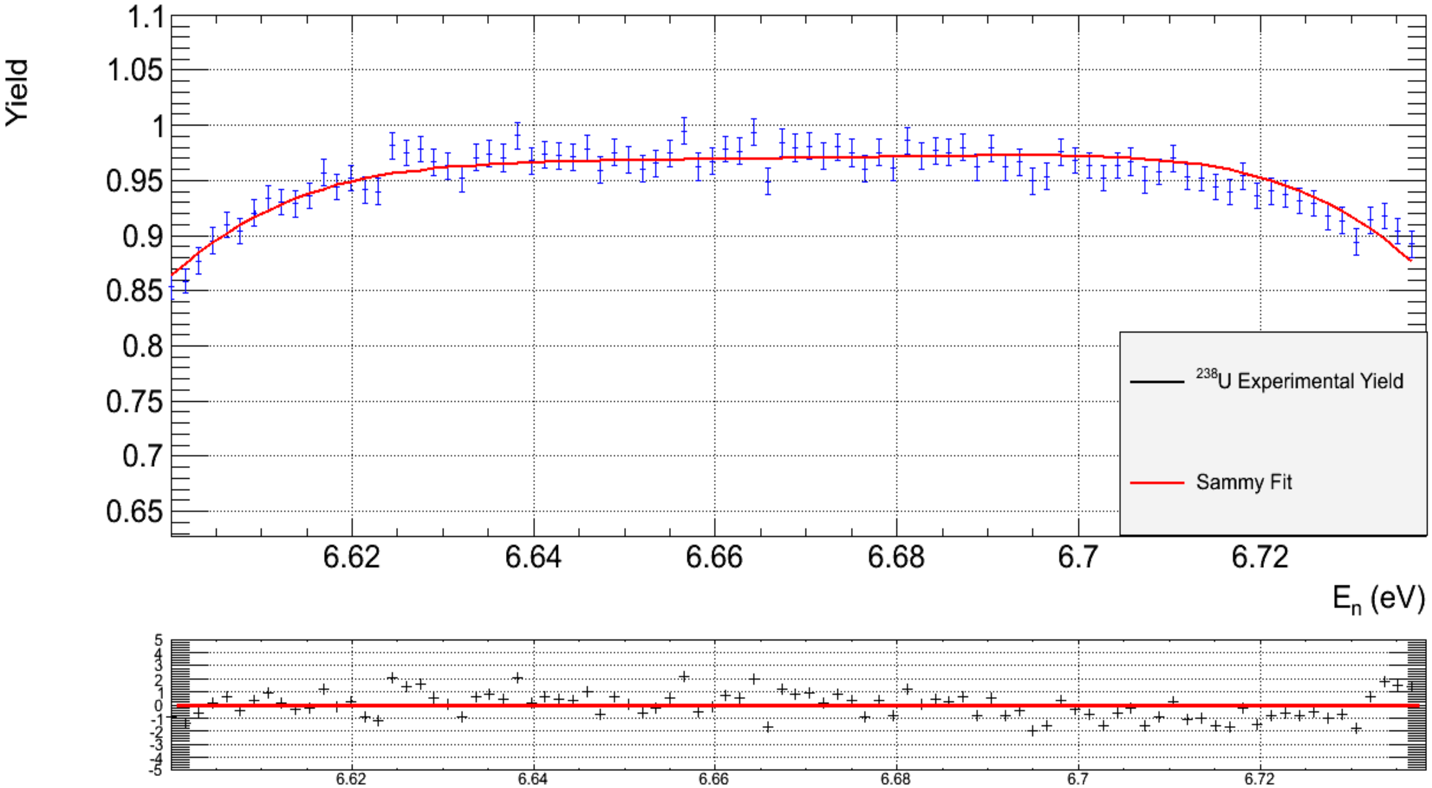
TOF

Chapter 3. Analysis: Calculation of the yield

$$Y(E_n) = \frac{C_{tot}(E_n) - C_{back}(En)}{N_{bif} \cdot \varepsilon \cdot \varphi(En)}$$

The product ($N_{bif} \cdot \varepsilon$) is determined by means of the *Saturated Resonance Method*.

The first **three** resonances are saturated, allowing three normalisation points to be used.
They all agree within 1 %.



Only low beam intensity pulses are used below 600 eV in order to minimise the pile-up.

Chapter 3. Analysis: Summary of Uncertainties

Some errors are given as intervals because they depend on each particular resonance, as for instance in the case of the dead-time correction, which depends on the counting rate reached at each resonance; and the neutron scattering background, which depends on the scattering to capture ratio of each resonance.

Source of uncertainty	Uncertainty	
	Below 1 keV	1-10 keV
Sample mass	0.03%	
Neutron flux (shape in E_n)[1]	1%	2%
Neutron flux (abs. value) [i.e. normalization][2]	1%	
Dead-time and pile-up correction[3]	0-1%	0%
Neutron scattering correction[4]	0-1%	0-2%
Background subtraction [other than (n,n)]	Negligible	
Overall	**1.4-2.0%**	**2.2-3.0%**

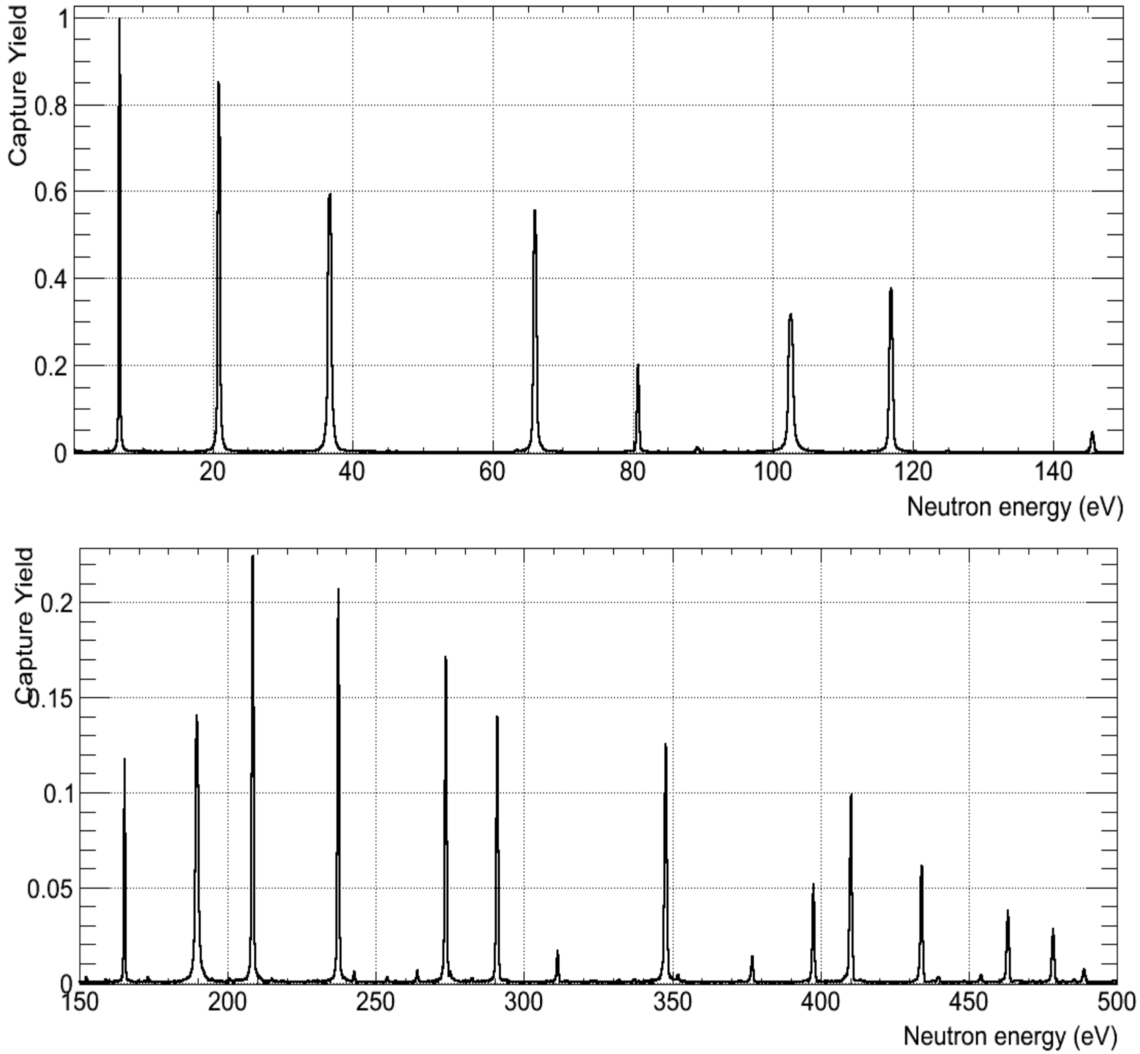
[1] See EPJ-A 49:27 (2013)

[2] The uncertainty is calculated from the agreement between SAMMY and the saturated region of the 1st resonance. The resonance parameters and multiple scattering correction have negligible effects.

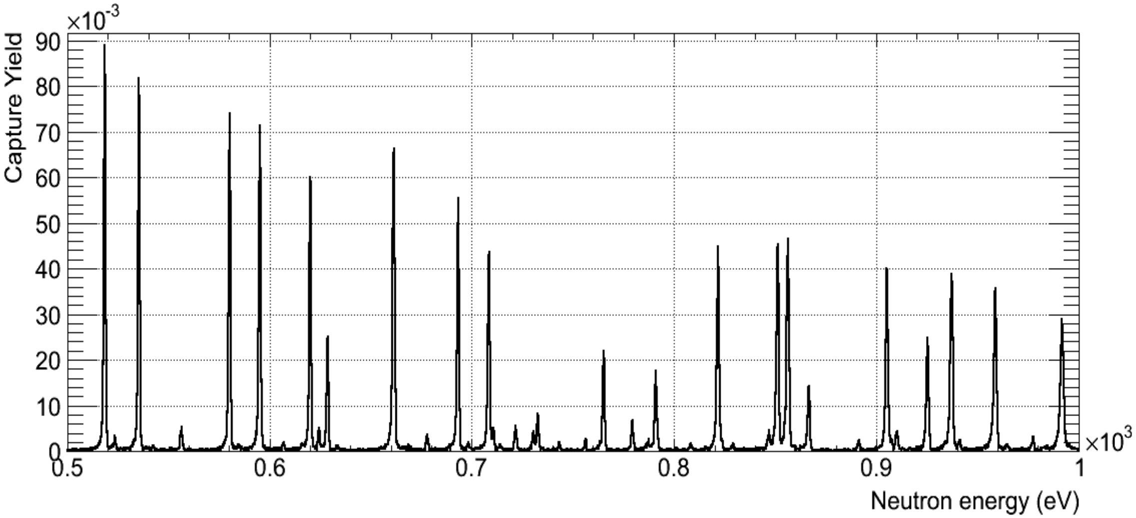
[3] The uncertainty regarding pile-up is estimated as the level of agreement at the peak of high counting rate resonances for low and medium beam intensity pulses after applying the dead-time and pile-up corrections.

[4] The uncertainty in neutron scattering background correction is difficult to quantify. We've assumed that this background can be calculated within 20%, and the maximum values for scattering contribution of the yield are ~10%, thus the 2% maximum uncertainty stated above.

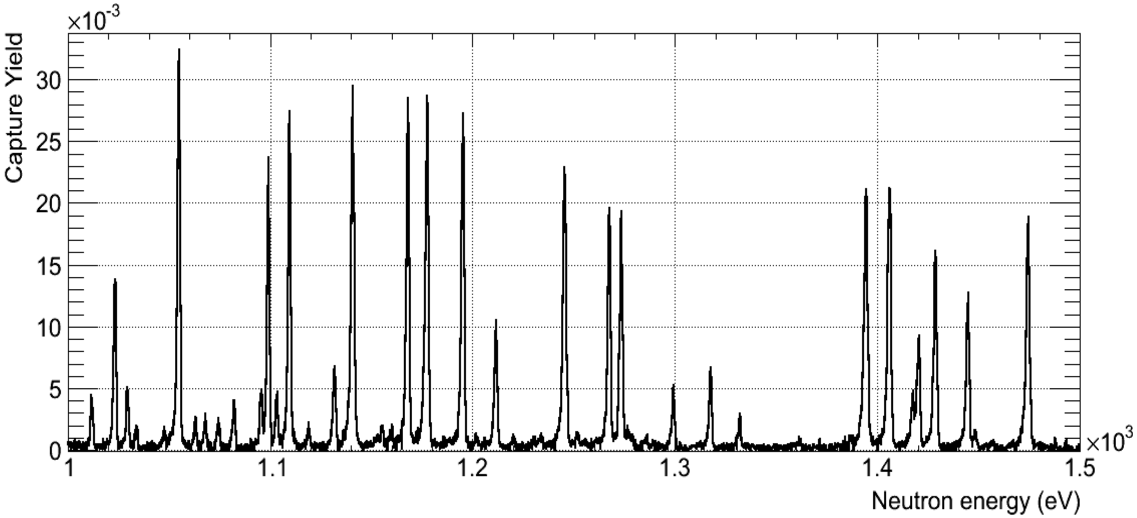
Results : TAC


Capture Yield
1
0.8
0.6
0.4
0.2
0
20
40
60
80
100
120
140
Neutron energy (eV)
Capture Yield
0.2
0.15
0.1
0.05
0
150
200
250
300
350
400
450
500
Neutron energy (eV)

Results : TAC

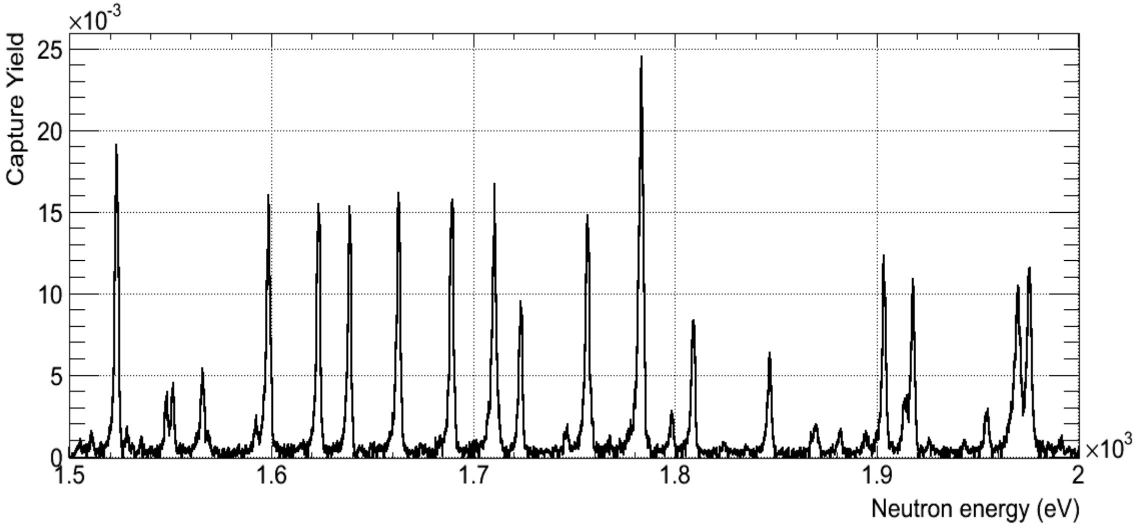


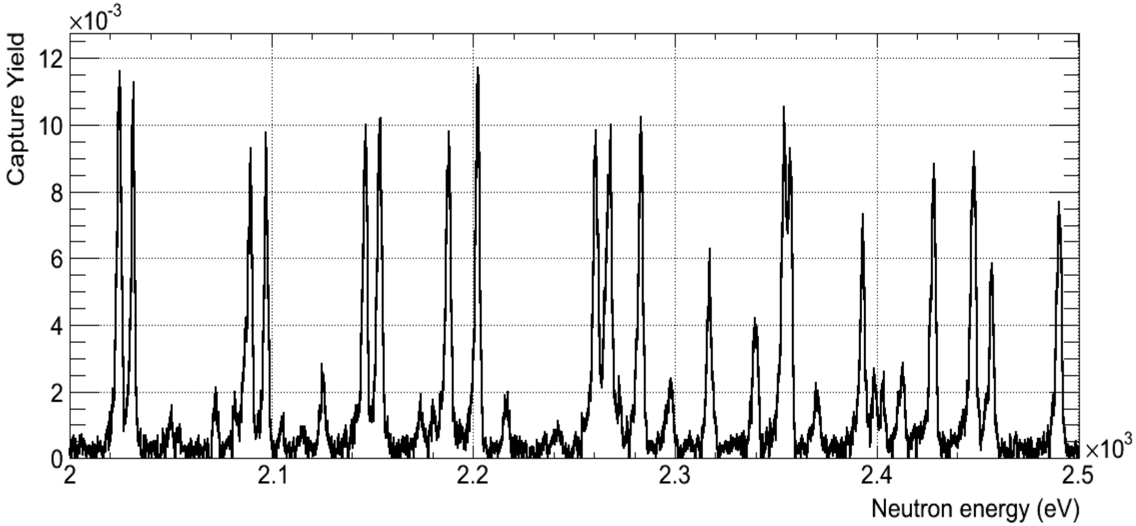
×10^-3
Capture Yield
90
80
70
60
50
40
30
20
10
0
0.5
0.6
0.7
0.8
0.9
1
×10^3
Neutron energy (eV)



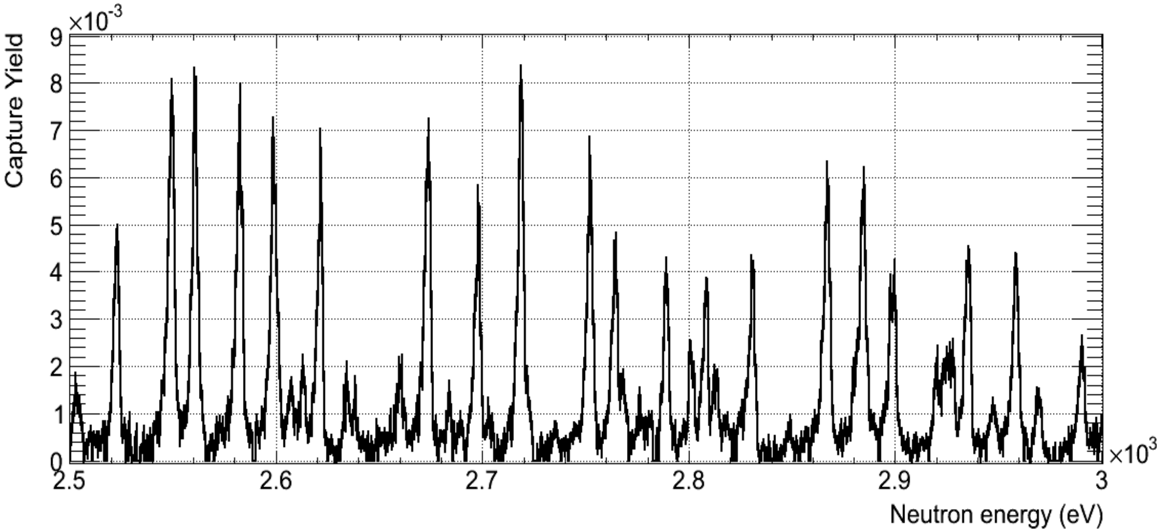
×10^-3
Capture Yield
30
25
20
15
10
5
0
1
1.1
1.2
1.3
1.4
1.5
×10^3
Neutron energy (eV)

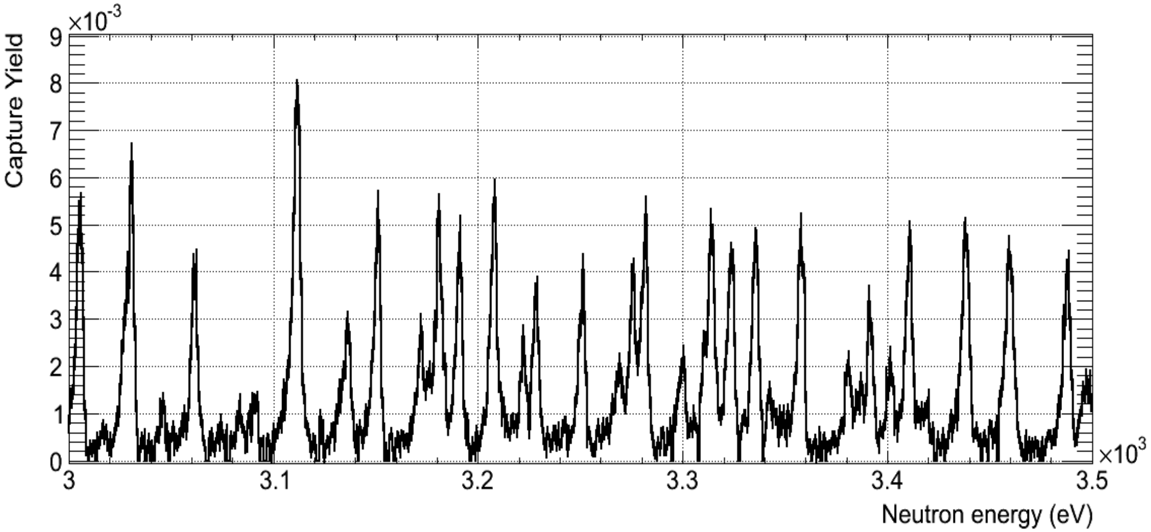
Results : TAC


×10-3
Capture Yield
0
5
10
15
20
25
1.5
1.6
1.7
1.8
1.9
2
×10³
Neutron energy (eV)

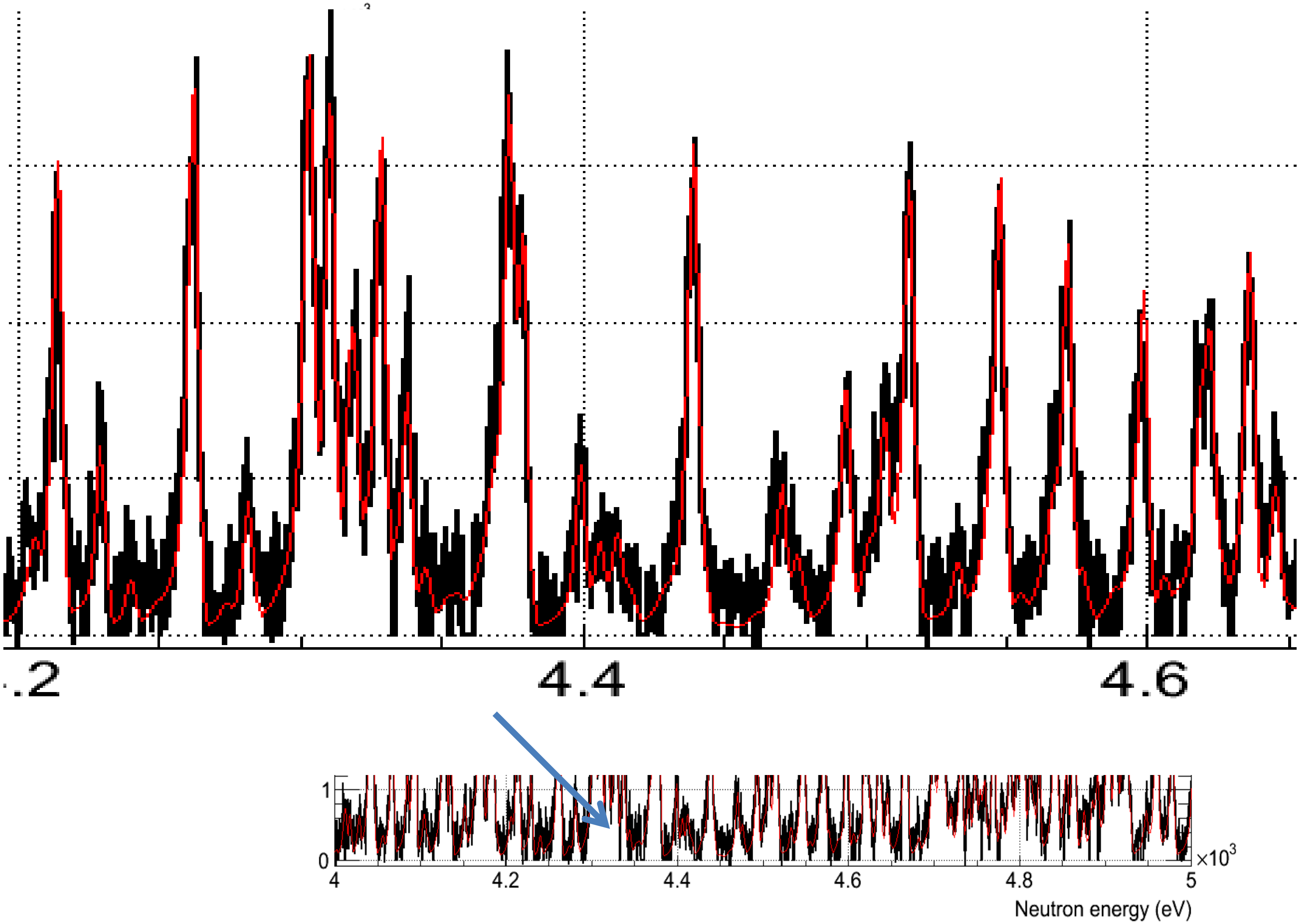

×10-3
Capture Yield
0
2
4
6
8
10
12
2
2.1
2.2
2.3
2.4
2.5
×10³
Neutron energy (eV)

Results : TAC

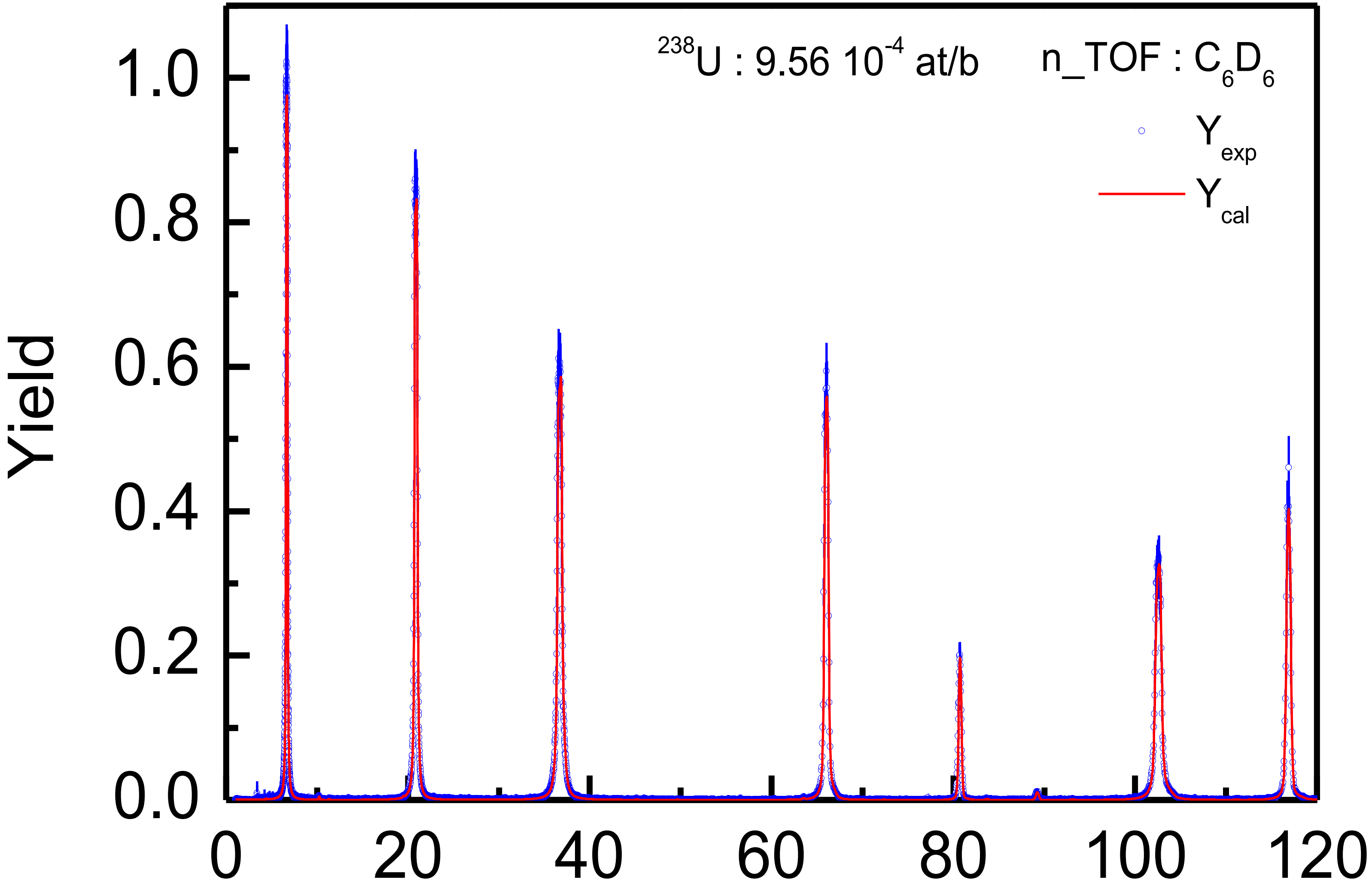

×10-3
Capture Yield
9
8
7
6
5
4
3
2
1
0
2.5
2.6
2.7
2.8
2.9
3
×10^3
Neutron energy (eV)


×10-3
Capture Yield
9
8
7
6
5
4
3
2
1
0
3
3.1
3.2
3.3
3.4
3.5
×10^3
Neutron energy (eV)

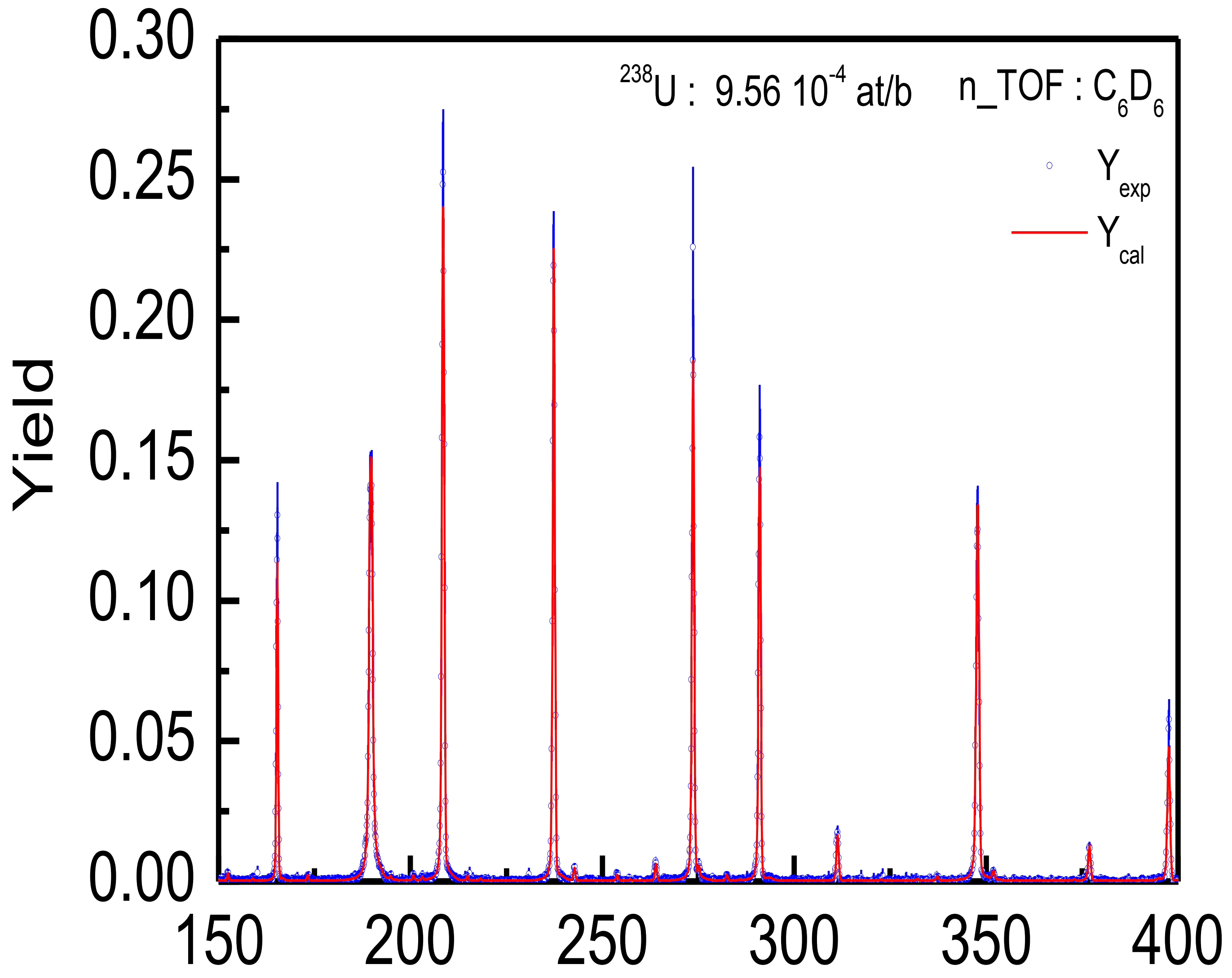
Results : TAC



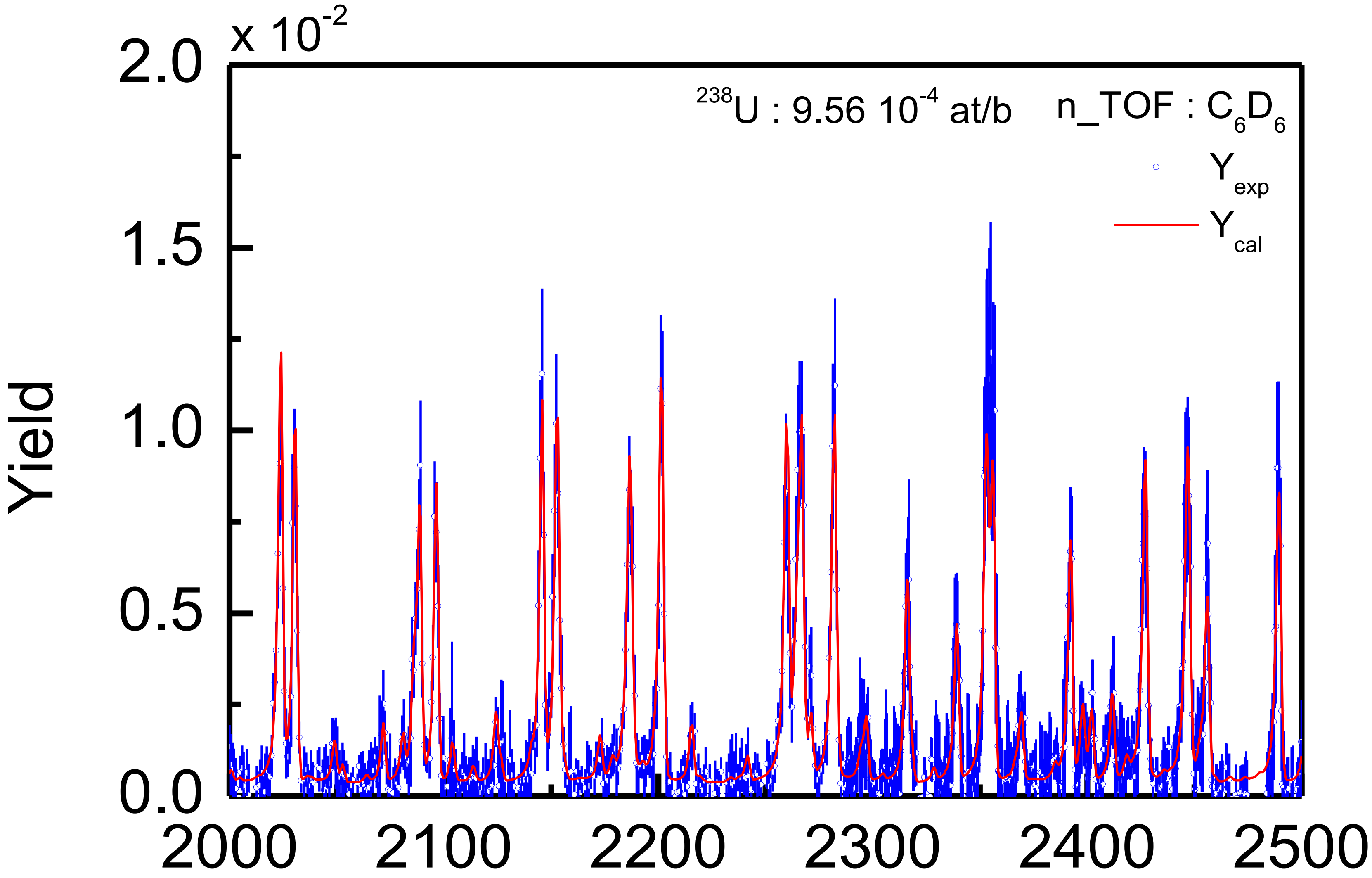
Results : C_6D_6



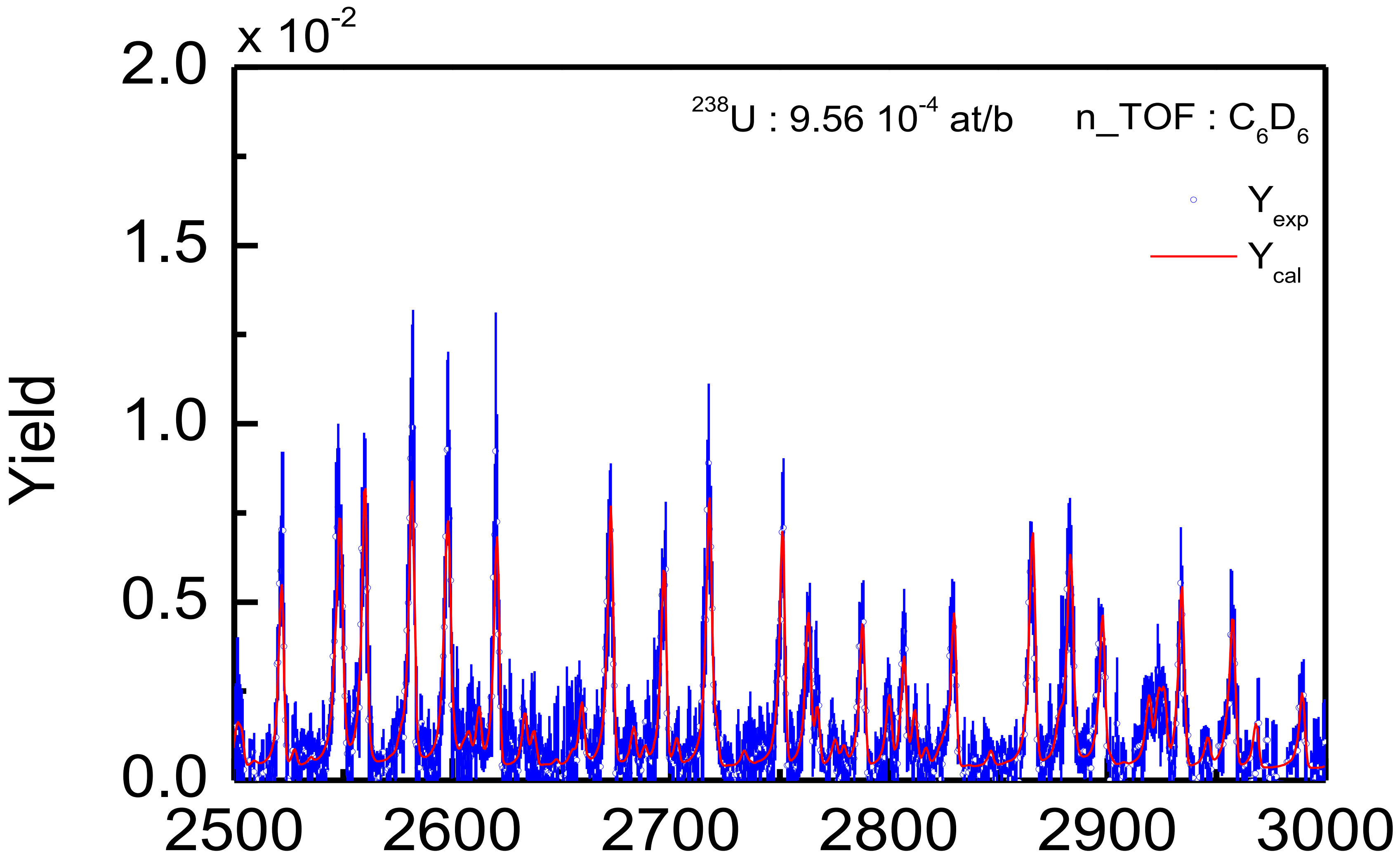
Results : C_6D_6



Results : C_6D_6



Results : C_6D_6



Conclusions

Within the ANDES project, a new measurement of the ^{238}U(n,γ) cross section has been performed at n_TOF using the 4π BaF_2 Total Absorption Calorimeter (TAC) and C_6D_6.

The results are of high quality thanks to:

- The use of measurement and analysis techniques well validated in previous n_TOF measurements.
- The high quality/purity of the sample
- The possibility of using the Saturated Resonance Method for normalization ($N_{bif} \cdot \varepsilon$)
- The development of an innovative pile-up and dead-time correction method for the TAC

The final accuracy of the TAC yield is:

Within 2% between 1 eV and 1 keV
Within 3% between 1 and 10 keV

The final accuracy of the C_6D_6 yield is:

Within 2% between 1 eV and 3 keV
Within 3% above 3 keV (unresolved region) (work in progress)

The resonance analysis will be completed in the immediate future for any future evaluations