

24^{ème} COLLOQUE GANIL

21 au 25 septembre 2026

Bussang, France



CaeSAR

CAEN, STRATÉGIE
POUR L'ACCÉLÉRATION
EN RECHERCHE



Measurement of the $^{19}\text{F}(n,\alpha)^{16}\text{N}$ cross section with the SCALP detector

The SCALP collaboration (LPC Caen, GANIL, EAMEA, CEA)

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L. Manduci (EAMEA)

X. Ledoux (GANIL)

O. Serot (CEA Cadarache)



GANIL



- **Motivations and scientific background**
- **Overview of the experimental setup**
- **E901 Experiment at NFS**
- **Data analysis**
- **Results on the $^{19}\text{F}(n,\alpha)^{16}\text{N}$ cross section with SCALP**
- **Conclusion and outlook**

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Neutron multiplication factor

$$k_{\text{eff}} \equiv \frac{\text{rate of neutron production}}{\text{rate of neutron loss}}$$

- **(n, α) reactions** of interest for nuclear reactors
- **Safety** optimisation: reactor modelling and fuel ageing
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→ **^{19}F** : Fluoride-based coolants in Molten Salt Reactors (4th Gen)

- $^{19}\text{F}(\text{n},\alpha)^{16}\text{N}$: **Uncertainties on reactor k_{eff}** ($\pm 40\text{-}130 \text{ pcm}^*$) [4]
- Validation of the experimental setup (large contribution of ^{19}F)

pcm = 'per cent mille' = $1\text{e-}5$

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- **¹⁹F(n,α)¹⁶N : Uncertainties on reactor k_{eff} (± 40 -130 pcm*) [4]**
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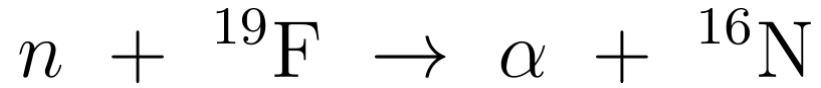
→ **¹⁶O** : Pressurized Water Reactors & Fast Neutron Reactors (3rd & 4th Gen) fuels/coolants

- **NEA : HPRL (ranked 2nd), WPEC 26 (2008) & 40 (2015) [2] [3]**
- **¹⁶O(n,α)¹³C :**
 - **Helium formation** in fuel cladding ($\pm 7\%$) [1]
 - **Uncertainties on k_{eff} (± 100 pcm) [1]**

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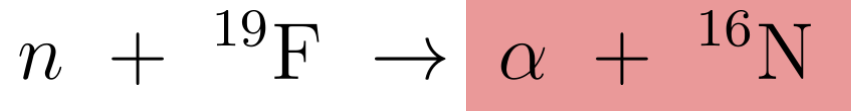


(n, α) CROSS SECTION ON ^{19}F



→ **Main methods for measuring the $^{19}\text{F}(\text{n},\alpha)^{16}\text{N}$ cross section :**

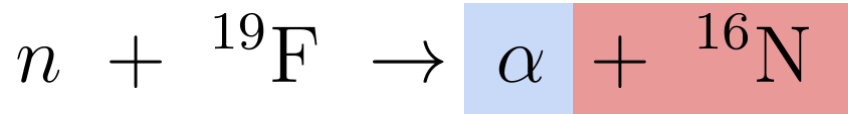
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- ionization chambers with active targets

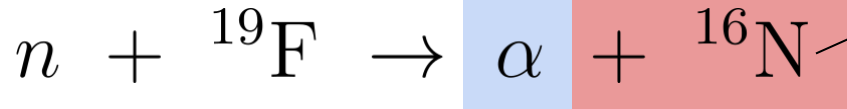
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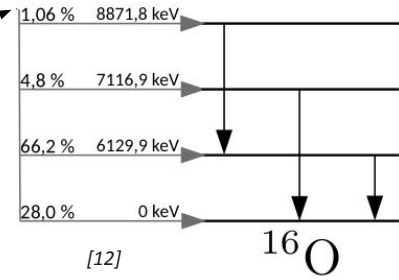
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- proportional counters or cloud chambers

(n, α) CROSS SECTION ON ^{19}F



$T_{1/2} = 7.13\text{s}$

β^-

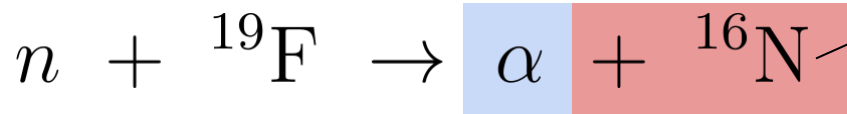


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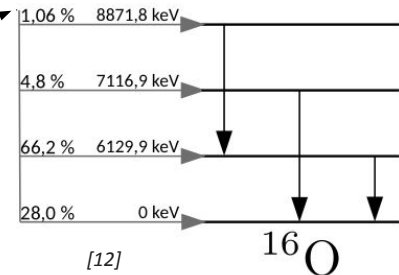
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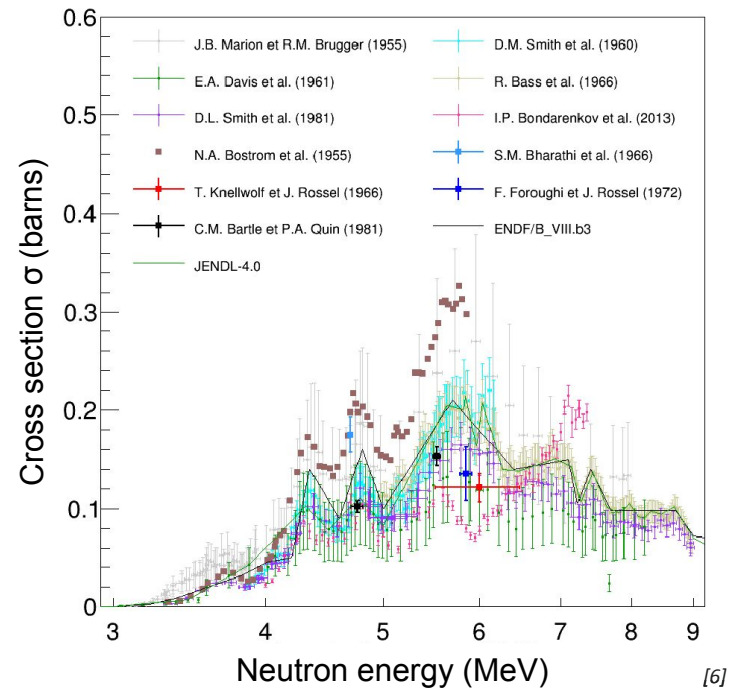
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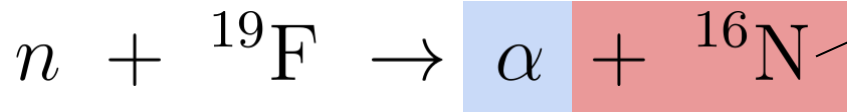
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→ Limits on evaluations

- Uncertainties from 12% to 40%, discrepancies up to 300% [7]
- sparse data above 9 MeV (no data between 9 and 13.5 MeV)

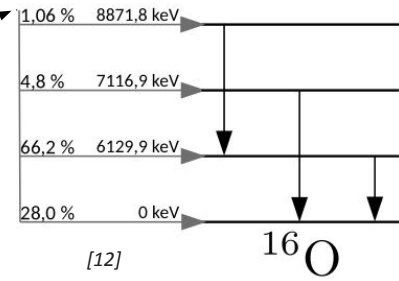


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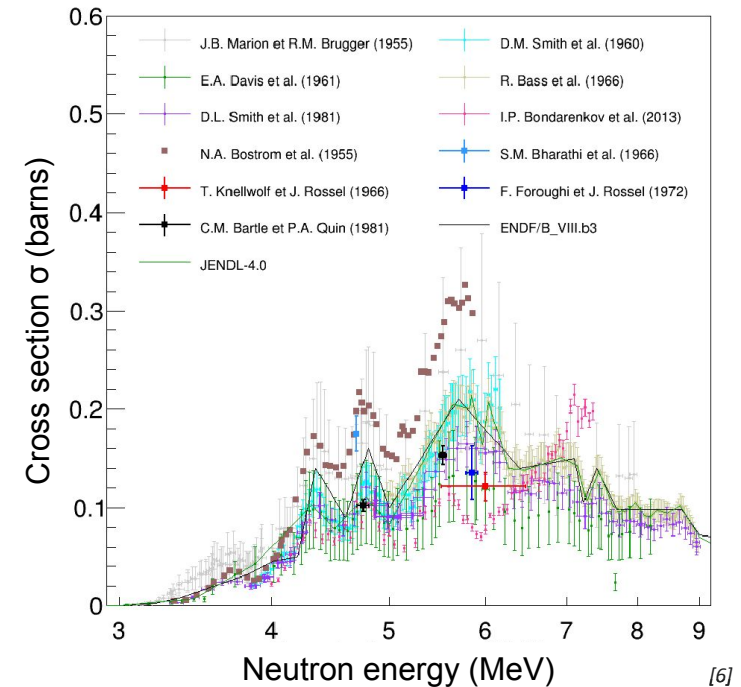
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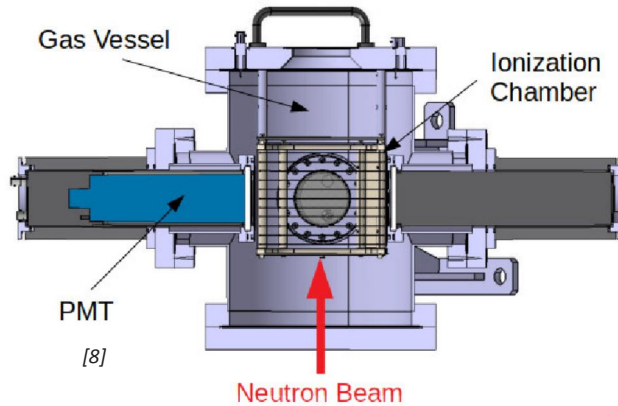
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provide new data sets for
the evaluation process
with SCALP



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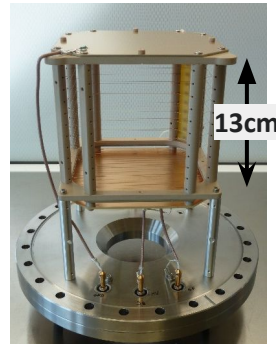
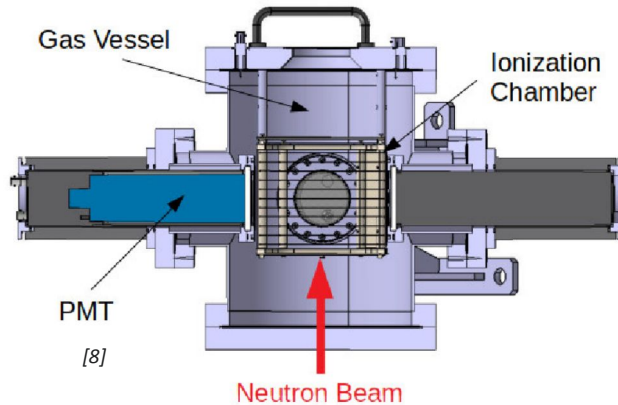
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Energy **deposited** by
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Ionization chamber

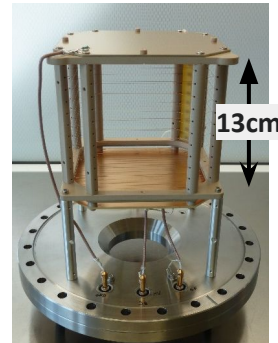
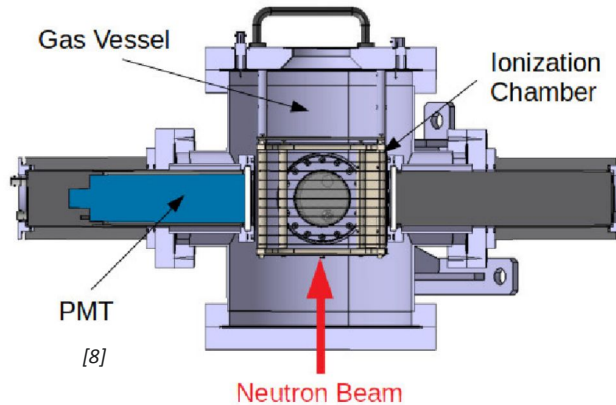
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4 photomultipliers

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Neutron kinetic energy
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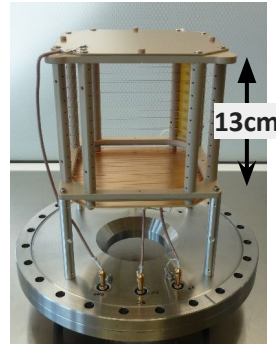
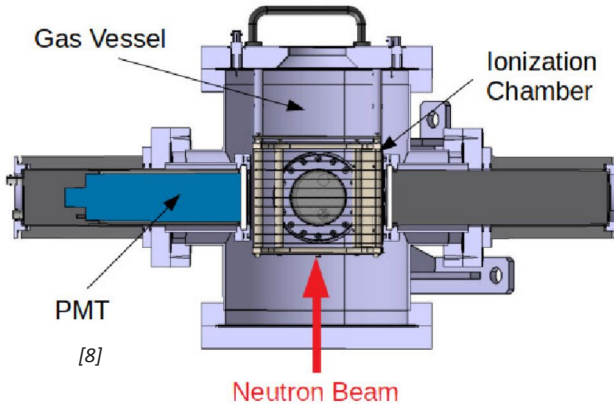
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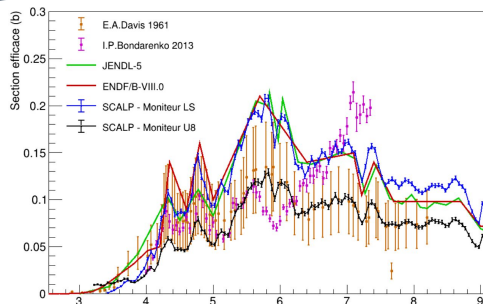
gas	IC energy resolution	timing resolution (PMTs)
CF_4	150 keV	600 ps
CF_4 (97%) + CO_2 (3%)	220 keV	> 700 ps

[8]

PREVIOUS SCALP EXPERIMENTS

Facility	NFS (2021)		nELBE (2022)	
Configuration	CF4	CF4 + CO2	CF4	CF4 + CO2
Duration (UT)	15	14	11	16
Data analysis	<i>A. Chevalier, PhD, 12/2024 [7]</i>	<i>not enough stat</i>	<i>ongoing</i>	<i>not enough stat</i>

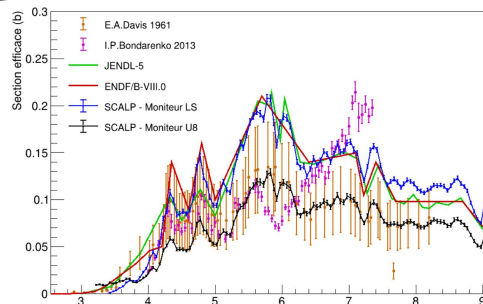
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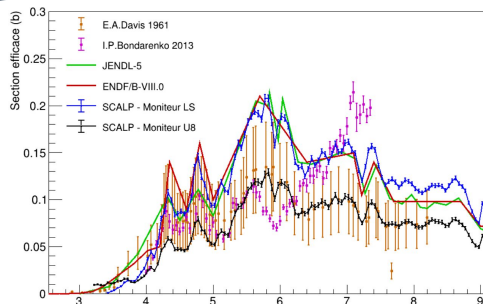
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- hydrogenated materials in the IC chathode
- **60% of the statistic lost** (prohibitive for $^{16}\text{O}(n, \alpha)^{13}\text{C}$)

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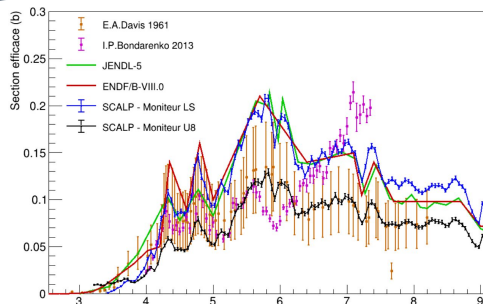
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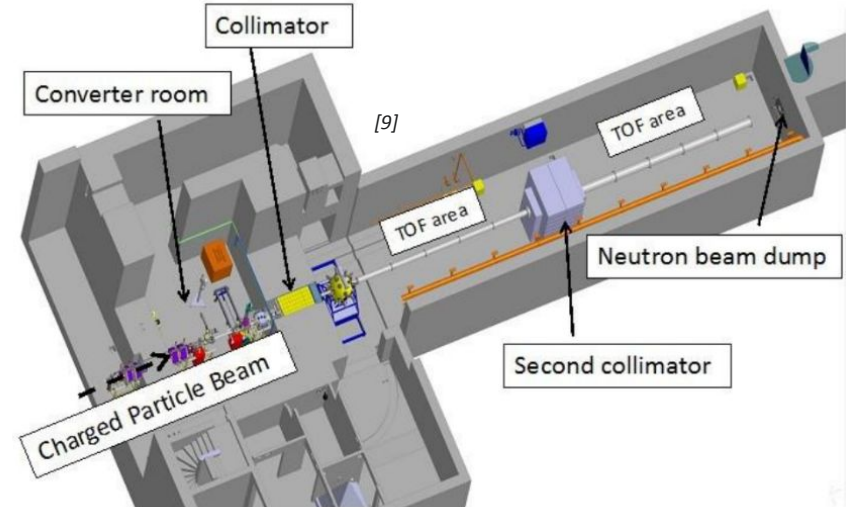
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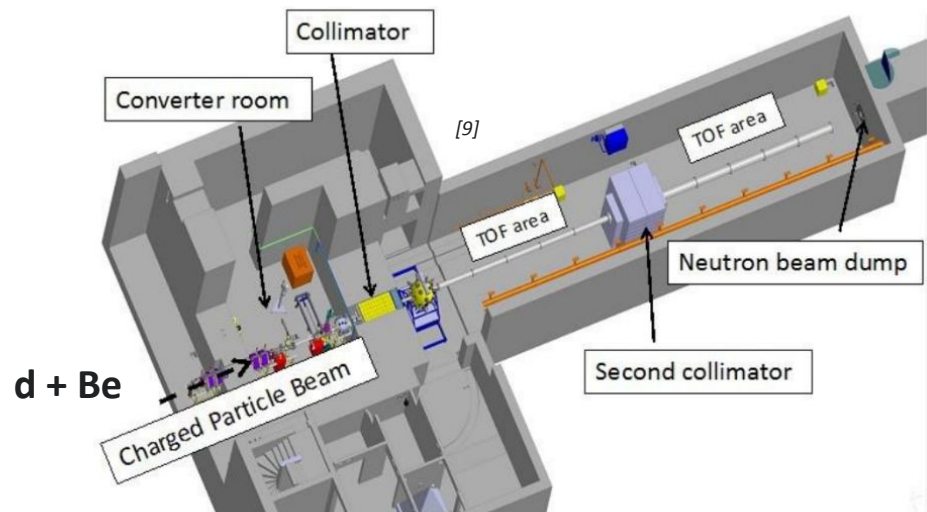
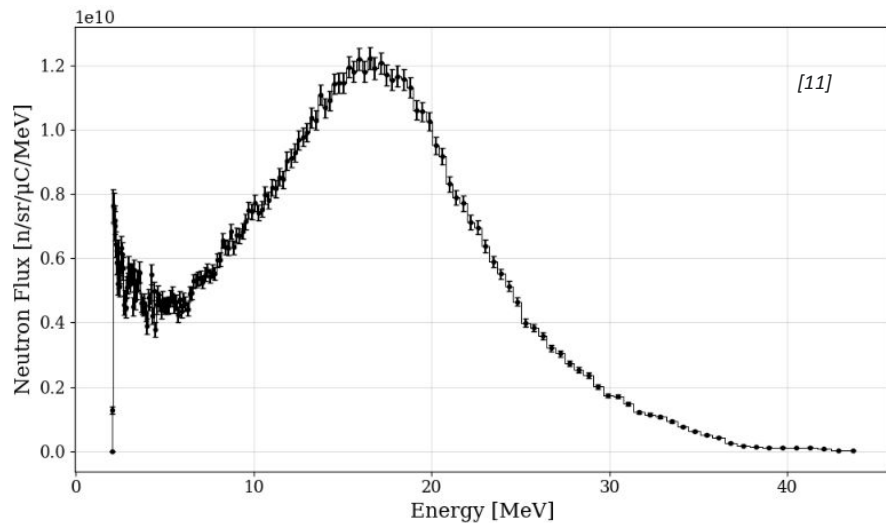
→ **SCALP modifications and improvement of the normalization procedure at NFS (SPIRAL2, GANIL)**

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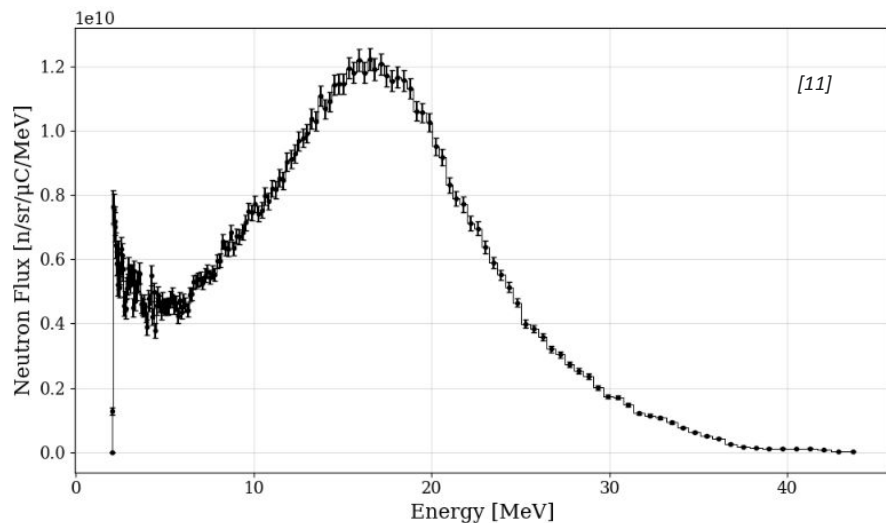
NFS = Neutrons For Science (SPIRAL2, GANIL) [9]

- ^2H beam (LINAG) @ 38 MeV on **Be** target
- Continuous energy distribution [1-44] MeV



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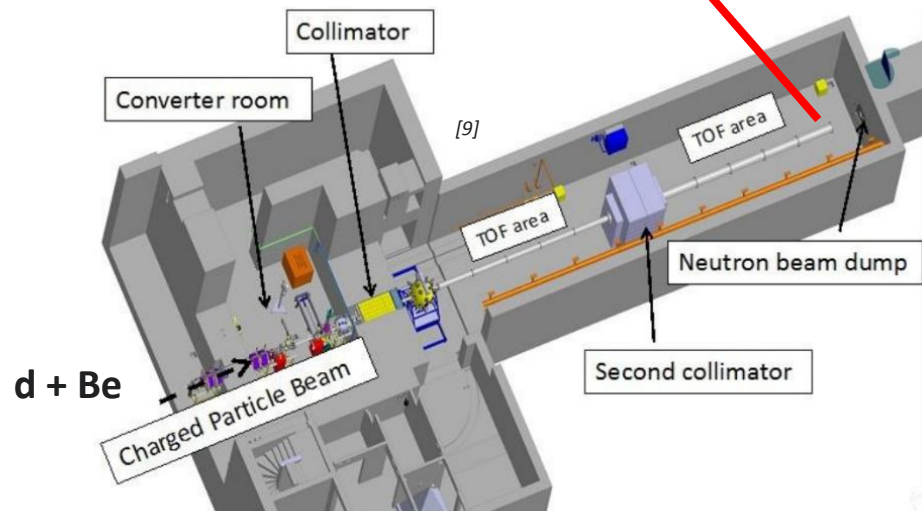
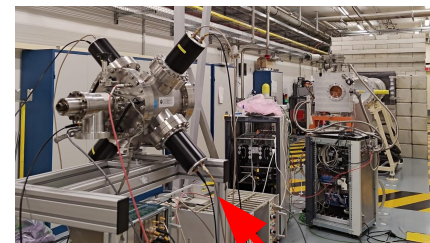


→ SCALP@NFS E901 (100% CF_4 - 14UT)

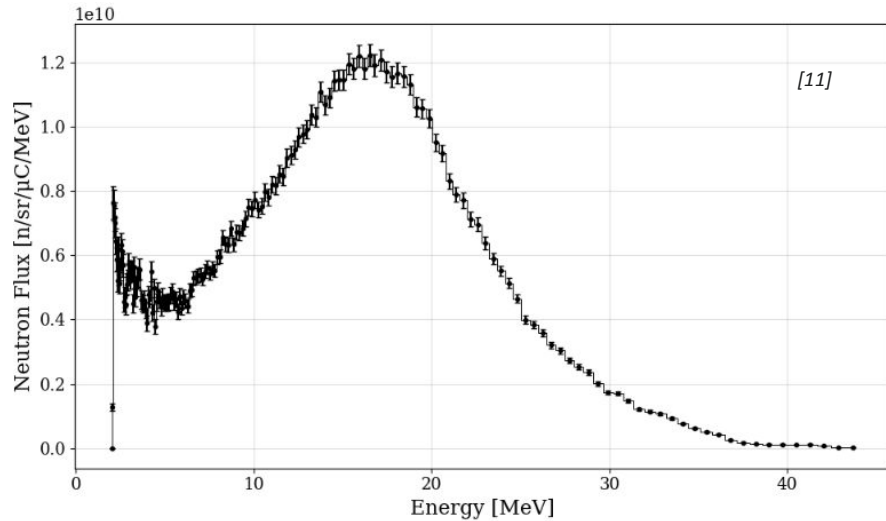
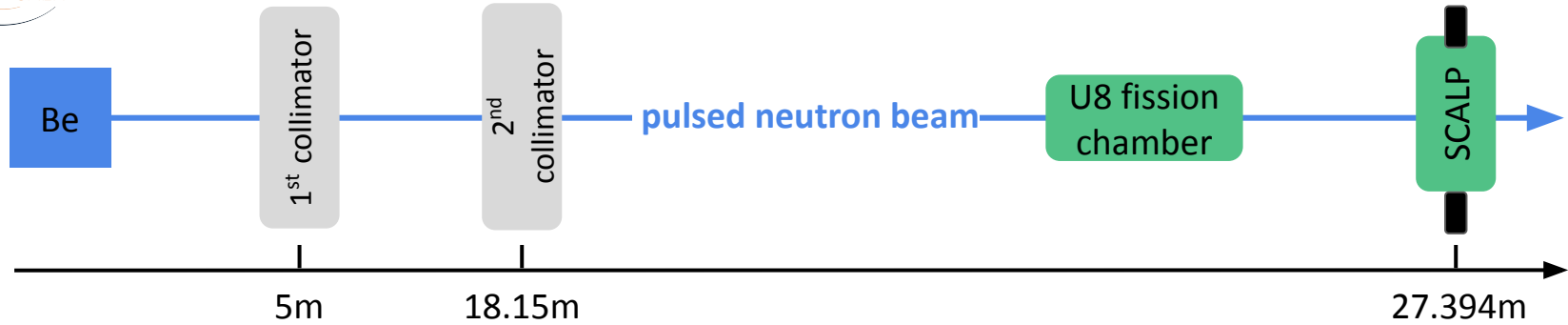
- primary HF 88MHz + beam chopper → $T_{\text{HF}} = 2.271 \mu\text{s}$
- flight distance : **27.394m**

→ small gamma flash

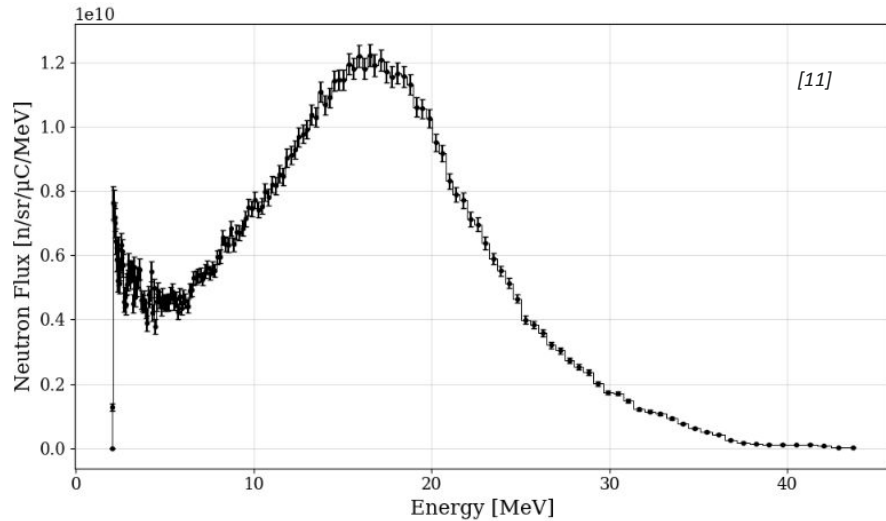
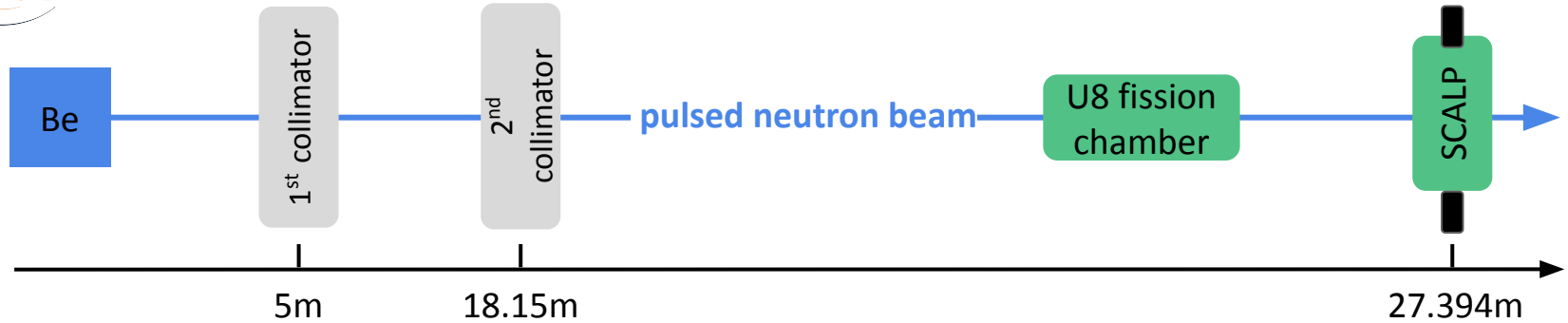
→ facility suited for the experiment



MONITORING OF THE NEUTRON FLUX

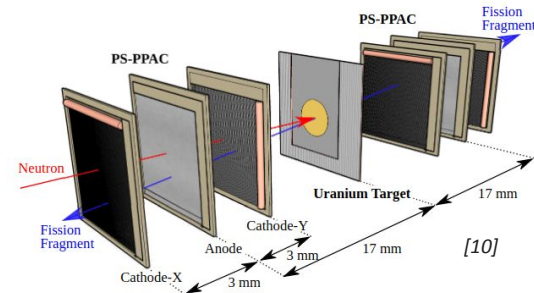


MONITORING OF THE NEUTRON FLUX



→ **Fission chamber** : detection of $^{238}\text{U}(n,f)$ fragments

- Position Sensitive PPACs for beam profile
- $^{238}\text{U}(n,f)$ cross section for the yield



→ *non intrusive*

→ *simultaneous operation*

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$$\text{ToF} = (t_{\text{PMT}} - t_{\text{HF}}) \bmod T_{\text{HF}}$$

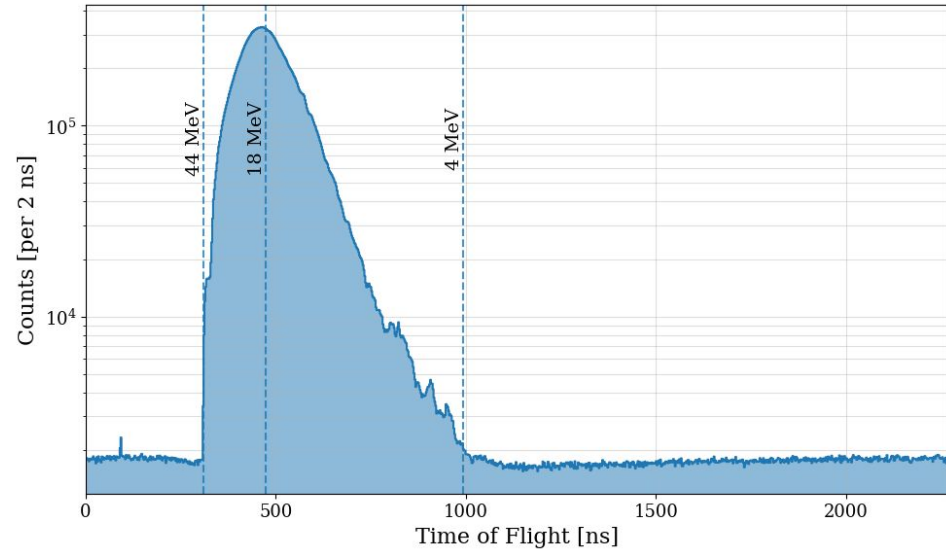
t_{PMT} $\nearrow$ PMT timestamp

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T_{HF} $\nwarrow$ HF period (2.271 μs)

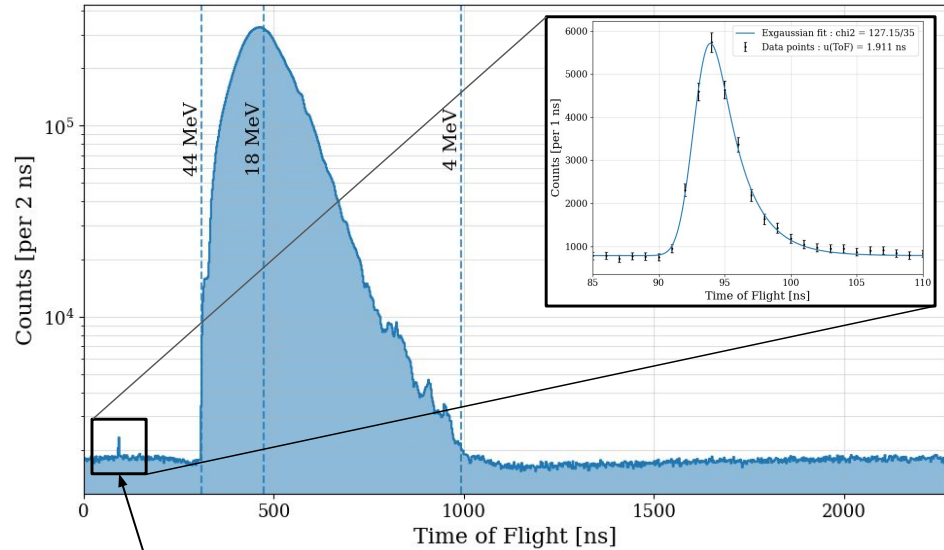
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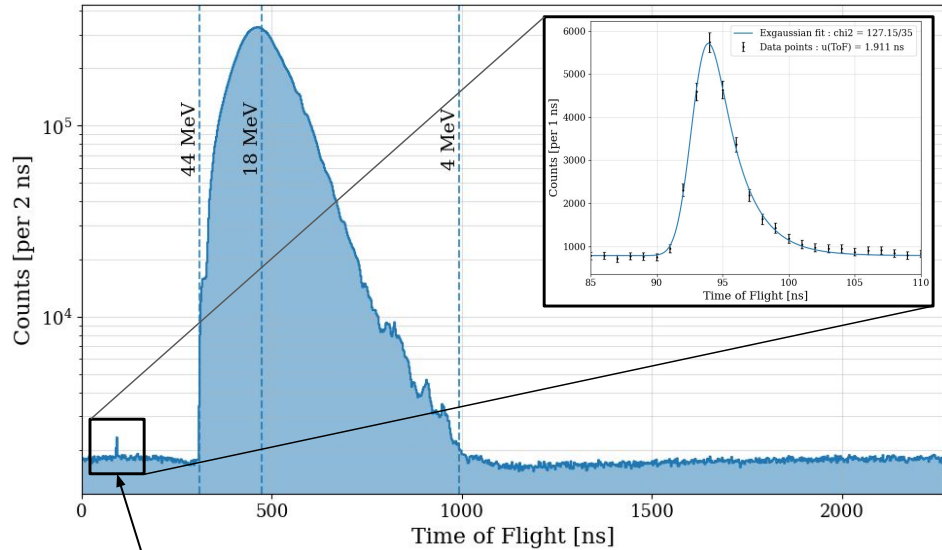
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γ flash (ToF reference) $\rightarrow$ ToF resolution < 2ns

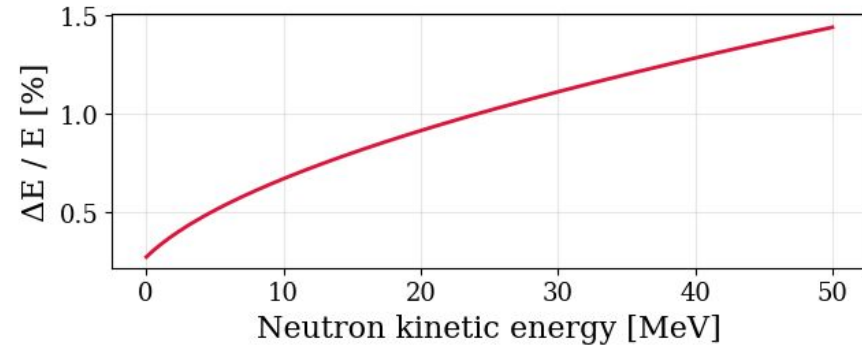
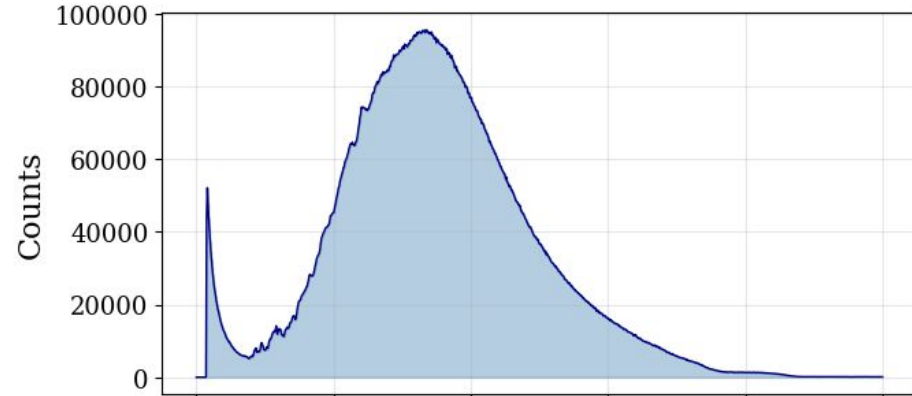
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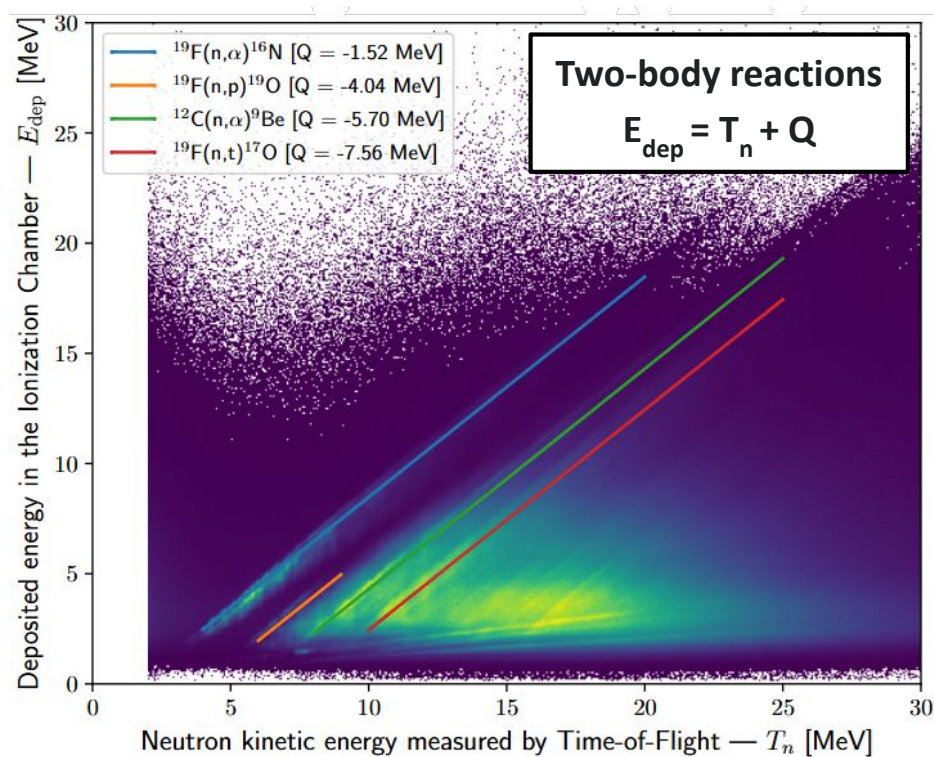
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$$T_n = (\gamma - 1)m_n c^2$$



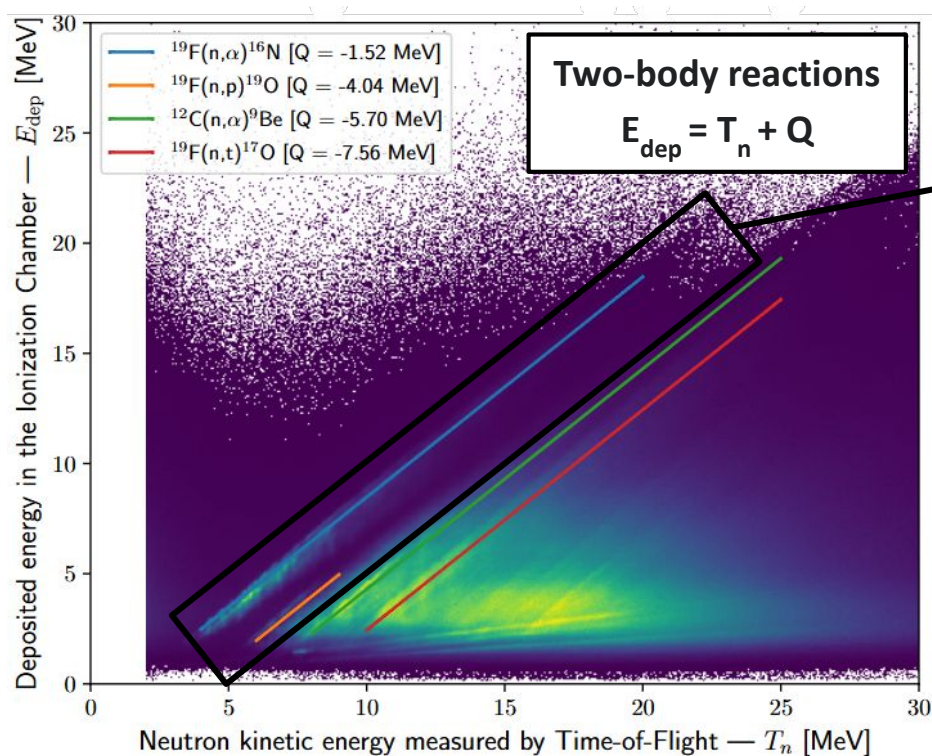
$\rightarrow$ Energy resolution **better than 1%** below 20 MeV

IDENTIFICATION OF REACTION CHANNELS

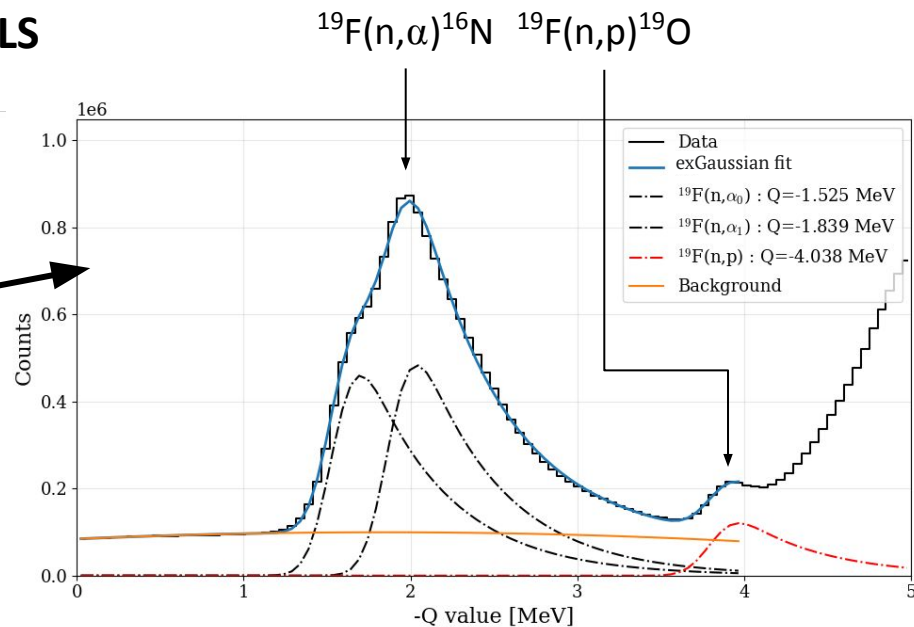


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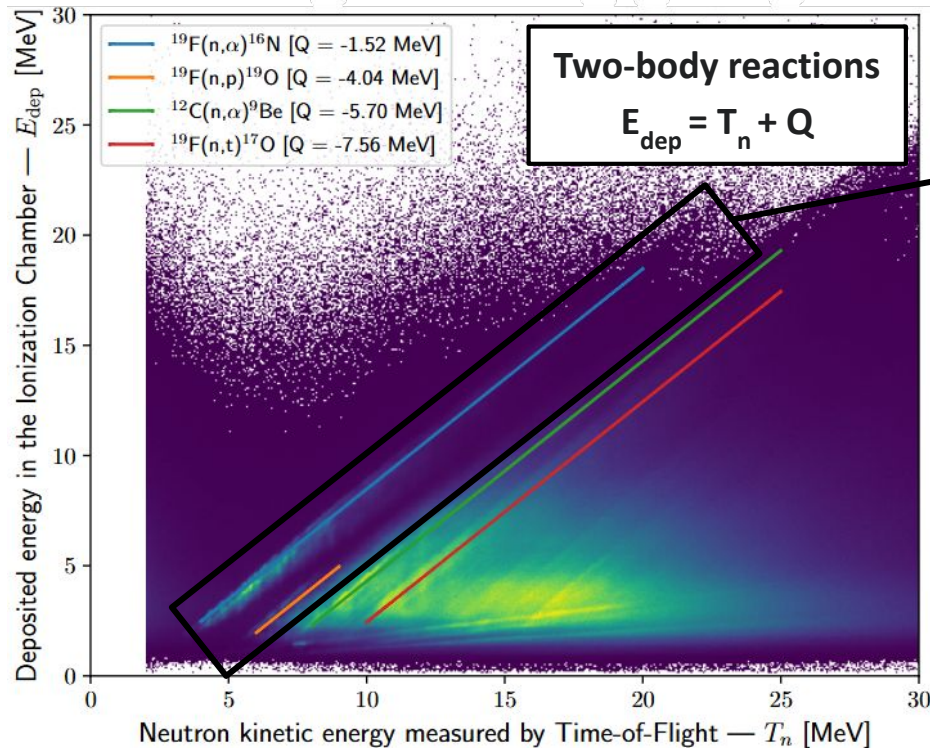


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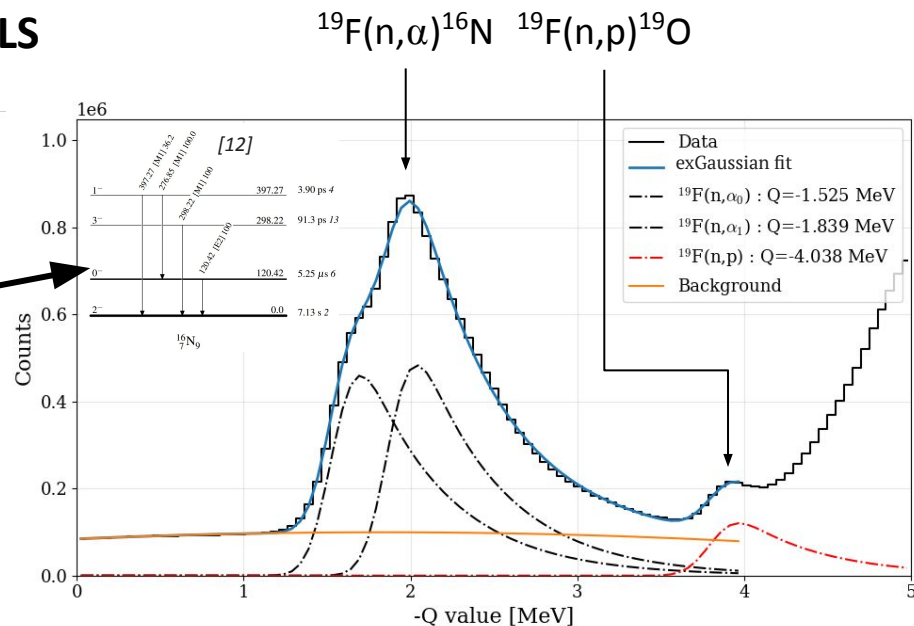


→ **Projection** along the reaction lines : Q_{val} spectrum

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→ **Projection** along the reaction lines : Q_{val} spectrum

→ Residual ^{16}N nucleus :

- 3 excited states below 400 keV : Q_{val} shift
- energy resolution : 2 effective states
- data matches with TALYS [13] calculations

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ESTIMATION OF THE CROSS SECTION

$$\text{cross section [cm}^2\text{]} \rightarrow \sigma(T_n) = \frac{N(T_n)}{\epsilon(T_n) \eta_{^{19}\text{F}} L \Psi(T_n)}$$

number of $^{19}\text{F}(n,\alpha)^{16}\text{N}$ events detected with SCALP $\rightarrow N(T_n)$
 detection efficiency (Geant4 simulation) [%] $\rightarrow \epsilon(T_n)$
 target nucleus density [cm $^{-3}$] $\rightarrow \eta_{^{19}\text{F}}$
 length of the detection zone [cm] $\rightarrow L$
 number of neutrons impinging the detector (beam monitor) $\rightarrow \Psi(T_n)$

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with :

$$\Psi(T_n) = \frac{\pi r^2}{d^2} \times Q_{\text{run}} \times \Phi_{FC}(T_n)$$

solid angle spanned by SCALP [sr] $\rightarrow \frac{\pi r^2}{d^2}$
 charge on the Be target [μC] $\rightarrow Q_{\text{run}}$
 neutron flux measured with the FC [n/sr/ μC] $\rightarrow \Phi_{FC}(T_n)$

ESTIMATION OF THE CROSS SECTION

$$\text{cross section [cm}^2\text{]} \rightarrow \sigma(T_n) = \frac{N(T_n)}{\epsilon(T_n) \eta_{^{19}\text{F}} L \Psi(T_n)}$$

number of $^{19}\text{F}(n,\alpha)^{16}\text{N}$ events detected with SCALP
 detection efficiency (Geant4 simulation) [%]
 target nucleus density [cm⁻³]
 length of the detection zone [cm]
 number of neutrons impinging the detector (beam monitor)

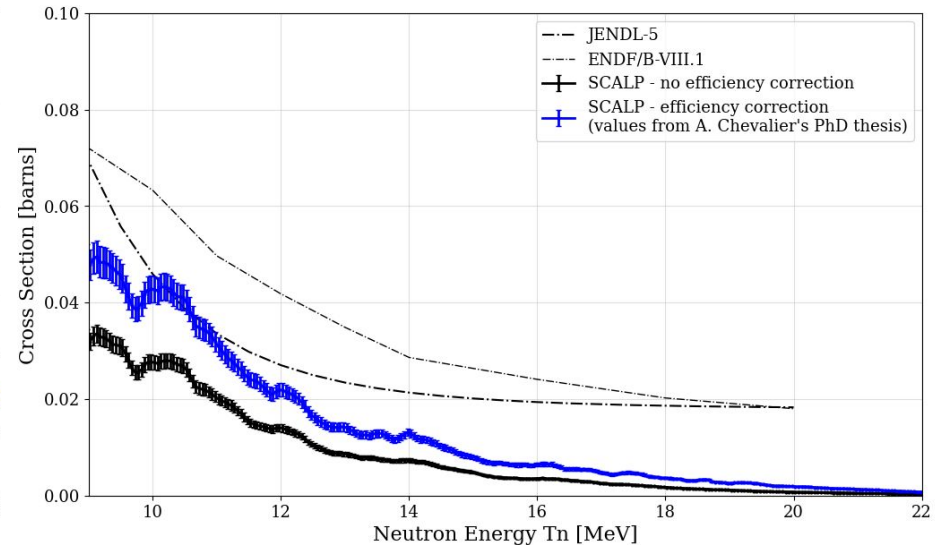
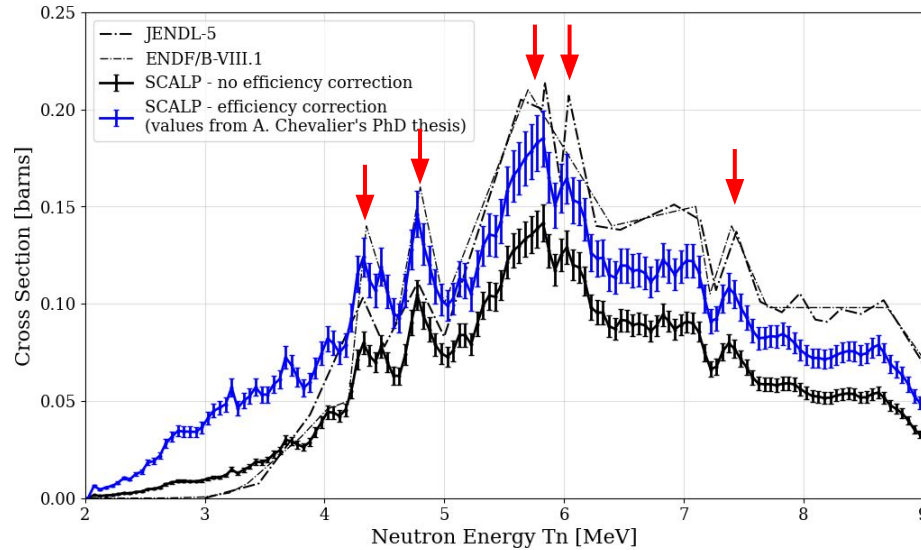
with :

$$\Psi(T_n) = \frac{\pi r^2}{d^2} \times Q_{\text{run}} \times \Phi_{FC}(T_n)$$

solid angle spanned by SCALP [sr]
 charge on the Be target [μC]
 neutron flux measured with the FC [n/sr/μC]

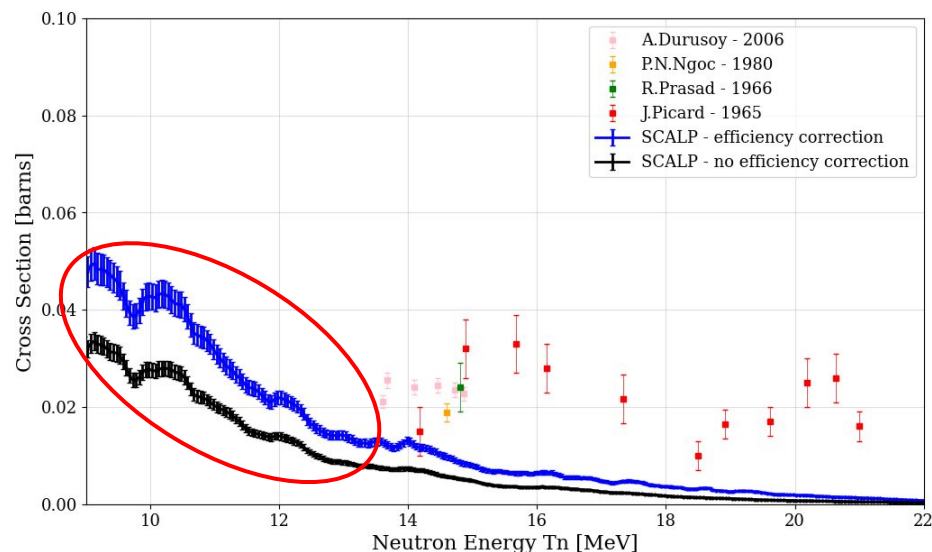
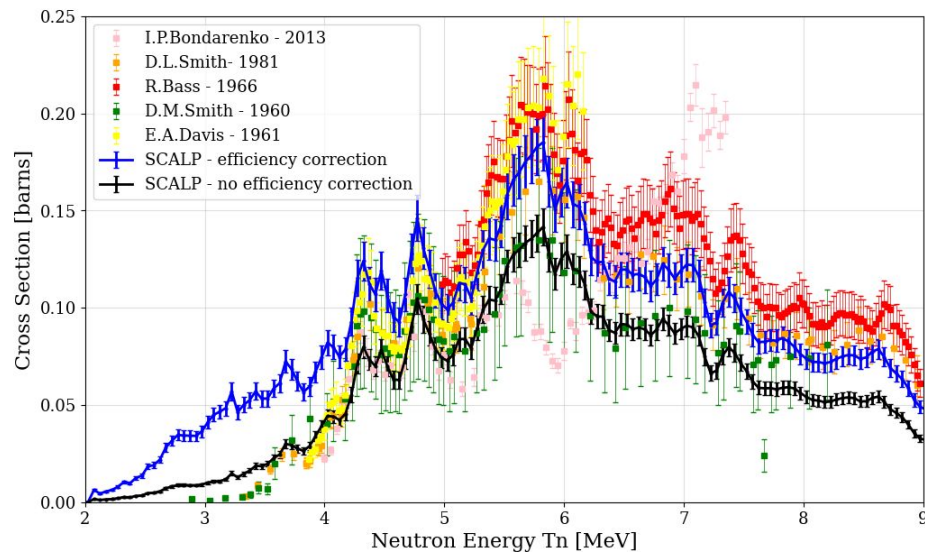
Quantity	Relative uncertainty (1σ) (%)
N (T _n)	0.54% - 4.12%
η _{19F}	1.99%
Φ _{FC} (T _n)	2.75% - 6.63%
r	1.60%

ESTIMATED $^{19}\text{F}(n,\alpha)^{16}\text{N}$ CROSS SECTION - vs evaluations



- **Uncertainty ranges from 5.28% to 7.98%** in the [2, 20] MeV range
- **Reproduction of expected structure at the right energies** (validation of energy reconstruction)
- **Preliminary results** : detection efficiency taken from previous experiment ([simulations ongoing](#))

ESTIMATED $^{19}\text{F}(n,\alpha)^{16}\text{N}$ CROSS SECTION - vs other measurements



- **Neutron energy resolution (<1%)** and **$u(\sigma)/\sigma$ (<8%)** are competitive, covering [2-20] MeV
- **Confirmation of newly observed structures with SCALP@NFS-2021, new data between 9 MeV and 13.5 MeV**
- **^{16}N excited states > 3 MeV** not accessible (identification matrix) : discrepancies above 10 MeV

- Motivations and scientific background
- Overview of the experimental setup
- E901 Experiment at NFS
- Data analysis
- Results on the $^{19}\text{F}(n,\alpha)^{16}\text{N}$ cross section with SCALP
- **Conclusion and outlook**

Context

- (n,α) reactions impact nuclear reactor simulations
- new measurements are needed for evaluation

Status

- setup is validated experimentally
- analysis, Geant4 simulations ongoing

++ energy resolution, reaction identification

++ normalization procedure, $u(\sigma)/\sigma < 8\%$ achieved

Context

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→ $^{16}\text{O}(n, \alpha)^{13}\text{C}$: to be submitted to PAC 2026

++ previous results, preliminary simulations

+ optimizations to improve statistics

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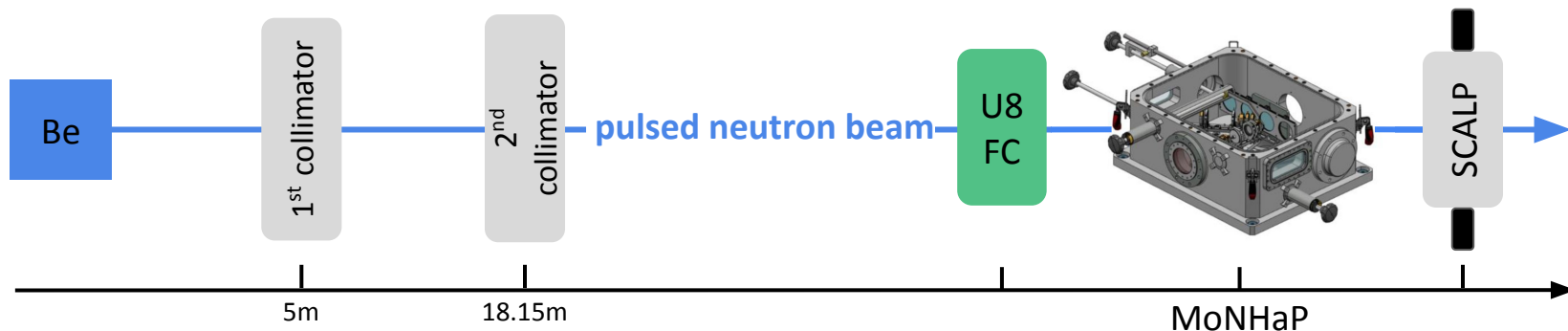
→ $^{16}\text{O}(n,\alpha)^{13}\text{C}$: to be submitted to PAC 2026

++ previous results, preliminary simulations

+ optimizations to improve statistics

→ **MoNHap** : non-intrusive **recoil proton spectrometer**

- normalization with the p(n,n)p cross section
- IAEA primary standard
- in-beam tests : 06/2026 (~33 UTs)
09/2026 (~26 UTs)



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Measurement of the $^{19}\text{F}(n,\alpha)^{16}\text{N}$ cross section with the SCALP detector

The SCALP collaboration (LPC Caen, GANIL, EAMEA, CEA)

N. Rousseaux, F.R. Lecolley, J.L. Lecouey, G. Lehaut, N. Marie, R. Lafaye, A. Chevalier (LPC CAEN)

L. Manduci (EAMEA)

X. Ledoux (GANIL)

O. Serot (CEA Cadarache)



GANIL



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- [2] OECD Nuclear Energy Agency - High Priority Request List (HPRL) <https://www.oecd-neia.org/dbdata/hprl/background.html>
- [3] Working Party on International Nuclear Data Evaluation Co-operation (WPEC). Nuclear Energy Agency (NEA) https://www.oecd-neia.org/icms/pl_23072/working-party-on-international-nuclear-data-evaluation-co-operation-wpec
- [4] S. Stjärnholm et al. « Nuclear Data Uncertainty Quantification for Reactor Physics Parameters in Fluorine-19-based Molten Salt Reactors ». In : EPJ Web of Conferences 294 (2024)
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- [8] G. Lehaut et al. « SCALP : a detector for (n,α) cross-section measurements ». In : EPJ Web of Conferences 225 (2020)
- [9] GANIL-SPIRAL2 FACILITIES, NFS-Neutrons For Science, <https://www.ganil-spiral2.eu/scientists/ganil-spiral-2-facilities/experimental-areas/nfs/>
- [10] D. Ramos et al. « A new beam monitor at NFS/SPIRAL2 based on position-sensitive PPACs detecting fission fragments from $^{238}\text{U}(n,f)$ », Nuclear Instruments and Methods in Physics Research Section A (2026)
- [11] X. Ledoux, Private communication
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CALIBRATION OF THE IONIZATION CHAMBER

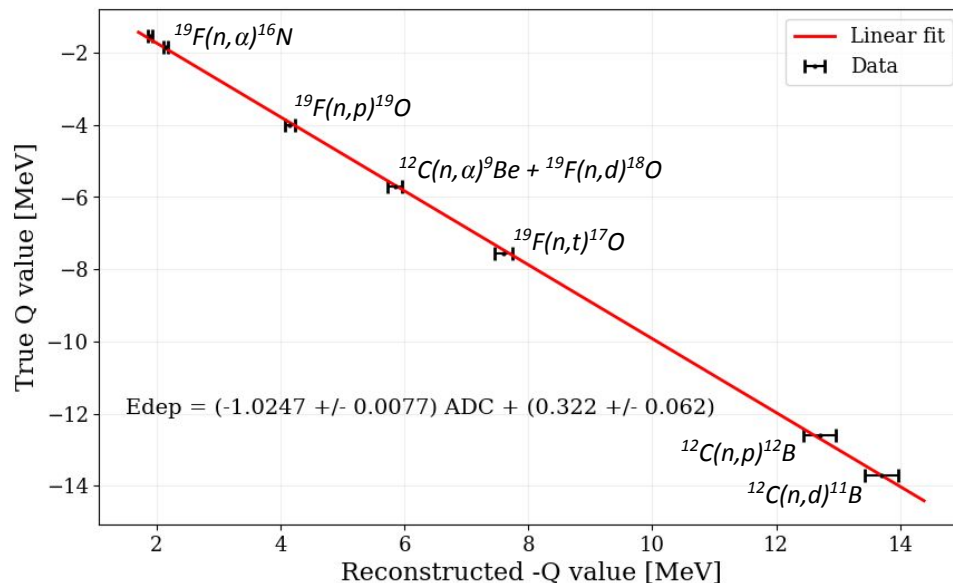
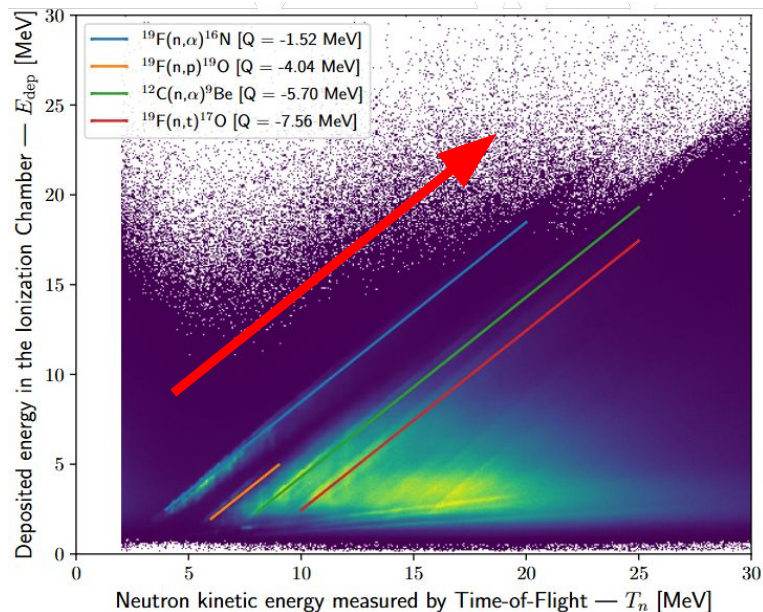
$$E_{\text{dep}} = a * \text{ADC} + b$$

-> slope a : PCA on the identification matrix

- diagonalize the covariance matrix

- principal variance direction (reaction lines) = eigenvector

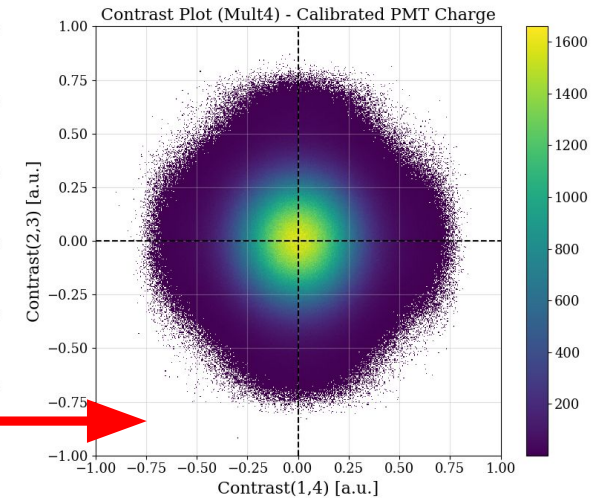
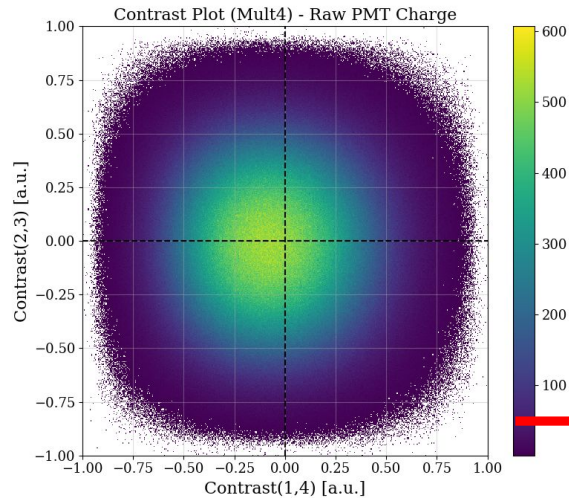
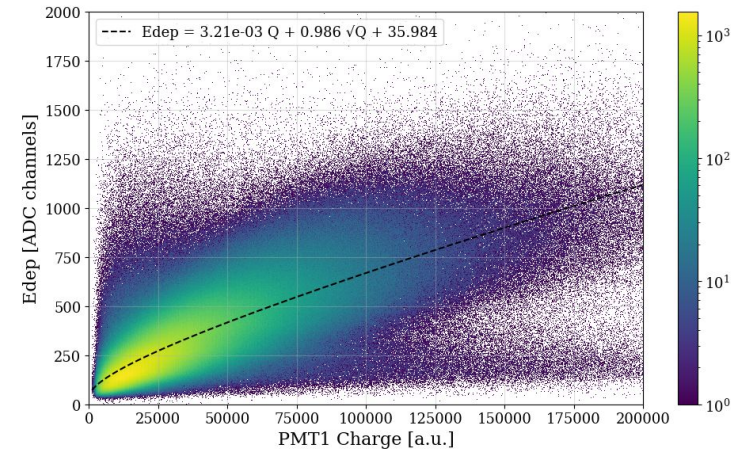
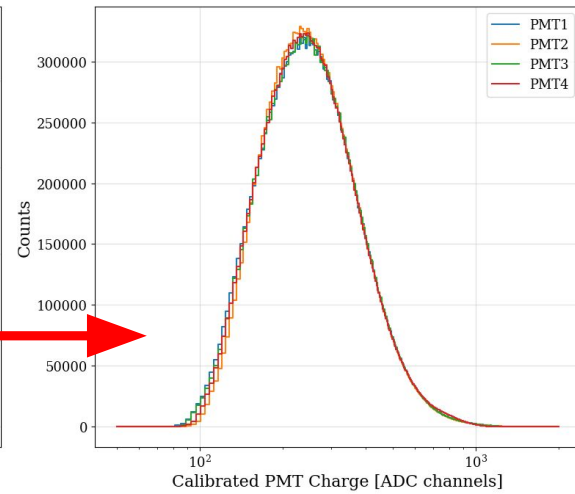
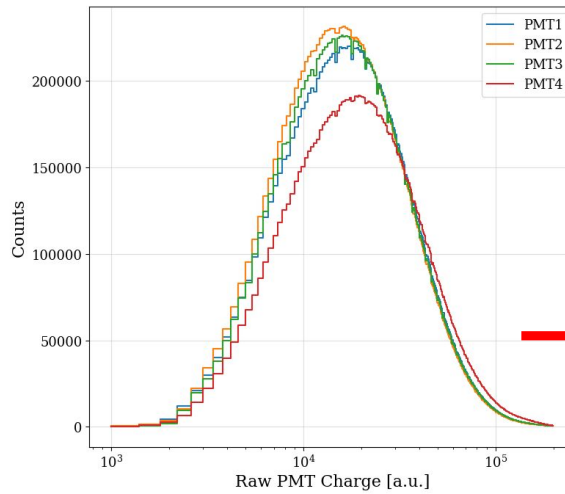
-> offset b : peak indexing on the Qval spectrum



-> PMTs are gain-matched on the IC with a polynomial fit

-> Contrast figure : pseudo-position in the transverse axis

$$C_{ij} = \frac{Q_i - Q_j}{Q_i + Q_j}$$

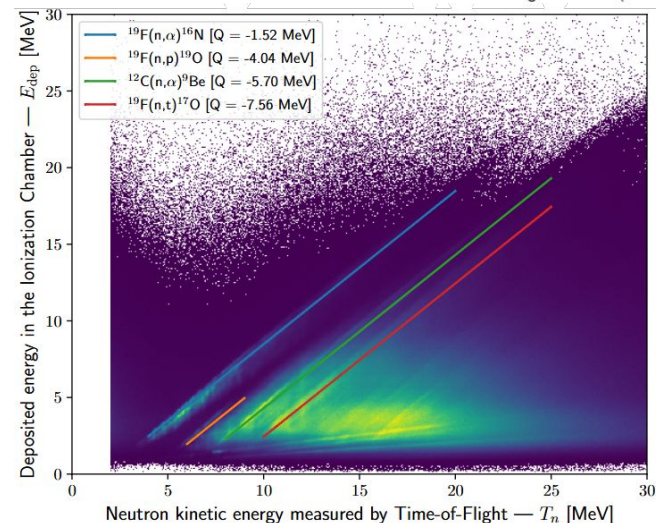
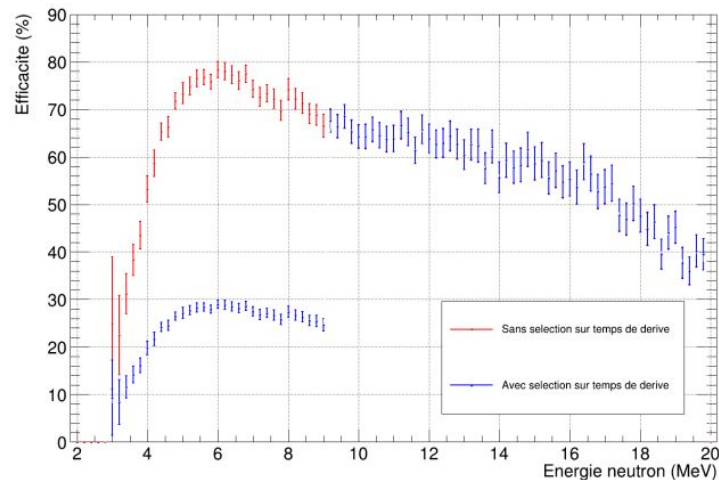
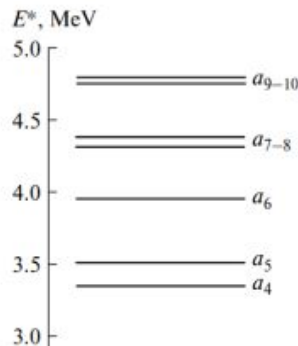


Below 4 MeV :

- efficiency values from 2021 : /!\ data contamination
- energy dependent cut : lower eff @ lower T_n
- new event selection : background substraction

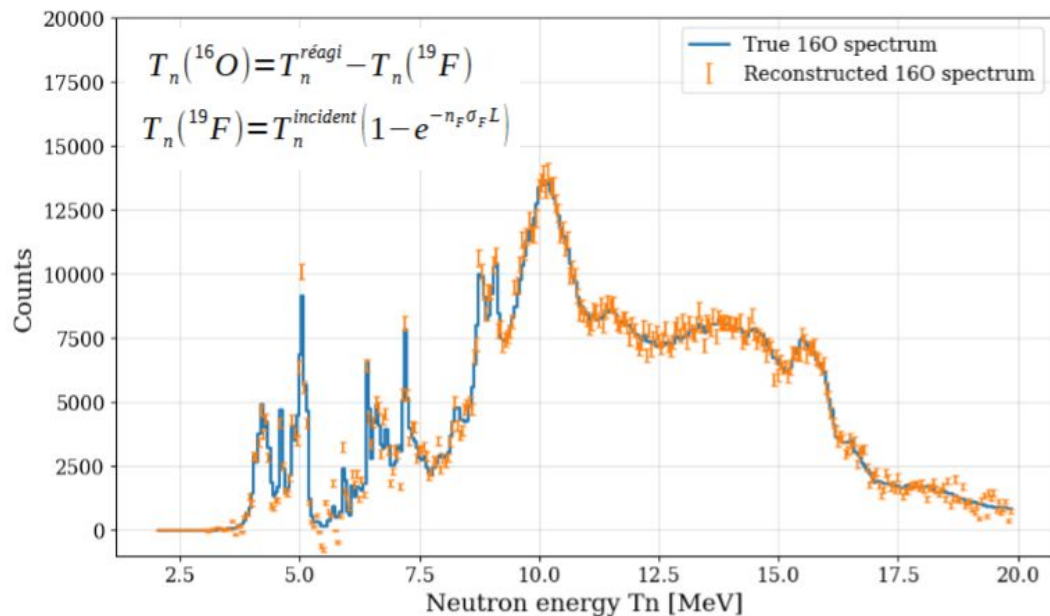
Above 10 MeV :

- ^{16}N excited states > 3 MeV
- not accessible with SCALP
- major contribution to the cross section

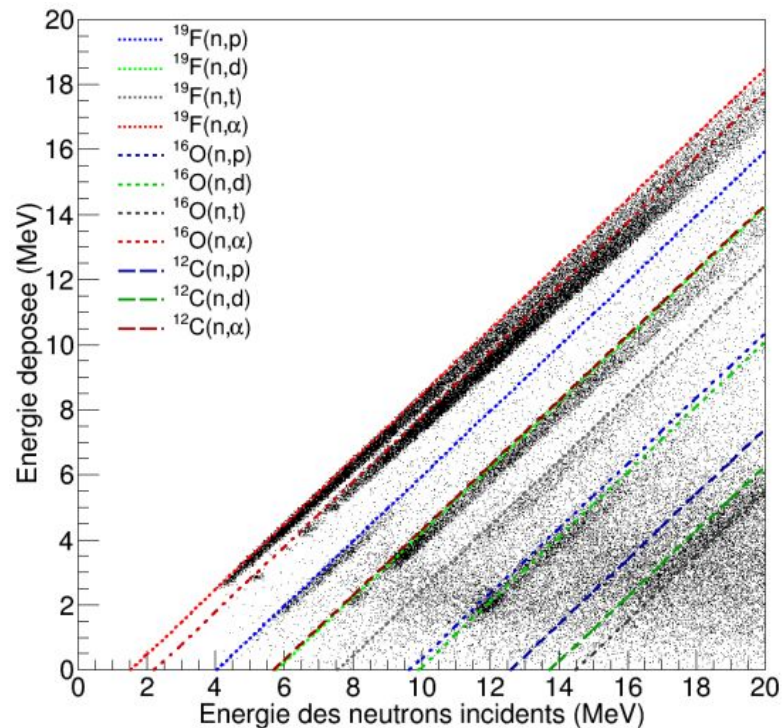


MEASUREMENT OF THE (n,a) CROSS SECTION ON 16O

- > Neutron energy spectrum deconvolution
- > 1e12 incident neutrons : 2.5% <stat error>



- $^{19}\text{F}(\text{n},\alpha)$: -1.525 MeV
- $^{16}\text{O}(\text{n},\alpha)$: -2.216 MeV
- > $\Delta = 750$ keV (400 keV with ES)



(n,α) CROSS SECTIONS ON ^{16}O AND ^{19}F

→ Main experimental methods

- ionization chambers with gaseous targets
- $\square$ or γ activation with scintillators, proportional counters, silicon detectors...

→ Limits on evaluations

- use of mono-energetic neutron sources : large systematic uncertainties
- sparse data above 9 MeV (no data for ^{19}F between 9 - 13.5 MeV)
- model dependant evaluations (ENDF, JENDL, ...)

→ Discrepancies up to **30% for ^{16}O** [1] and **300% for ^{19}F** [7]

large discrepancies...

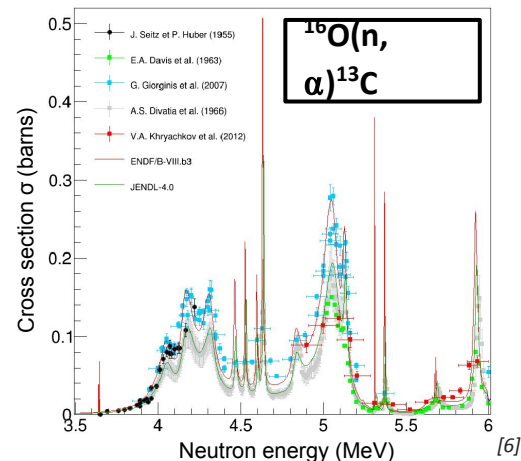
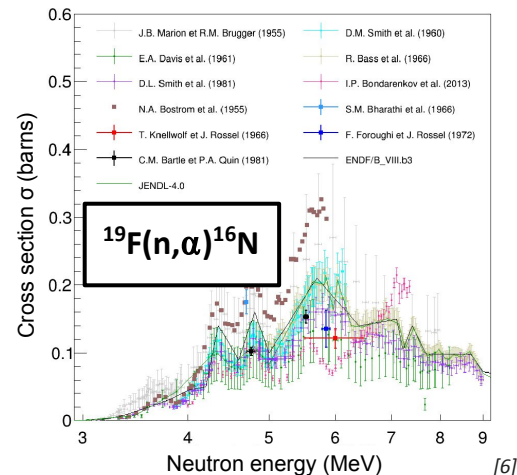
- *measurement vs measurement*
- *measurement vs evaluation*
- *evaluation vs evaluation*

...stress the need for new measurements

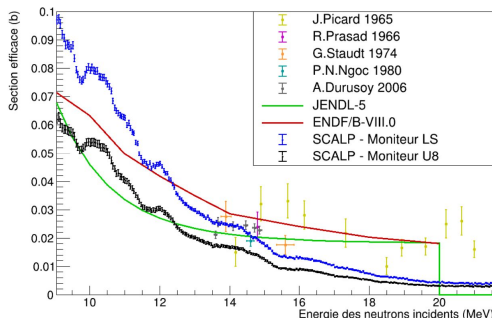
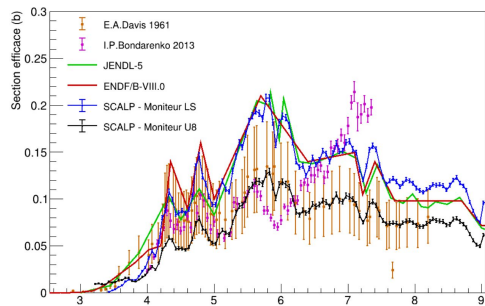
- *with new setups*
- *at several facilities*



**provide new data sets for
the evaluation process with
SCALP**

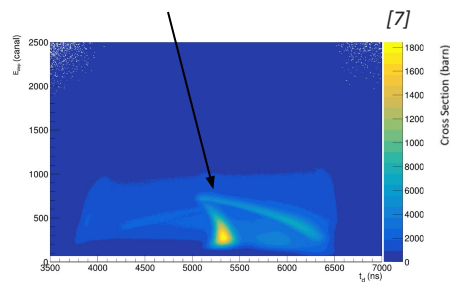


Facility	NFS (2021)		nELBE (2022)	
Configuration	CF4	CF4 + CO2	CF4	CF4 + CO2
Duration (UT)	15	14	11	16
Data analysis	A. Chevalier, PhD, 12/2024 [7]	not enough stat	ongoing	not enough stat

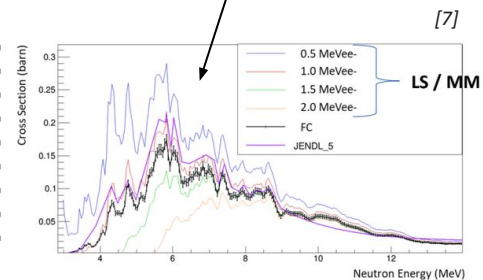


→ First measurements of (n,a) cross sections with the SCALP detector, A. Chevalier, PhD Thesis, 2024 [7]

data contamination by $p(n,n)p$



cross section with different normalization values



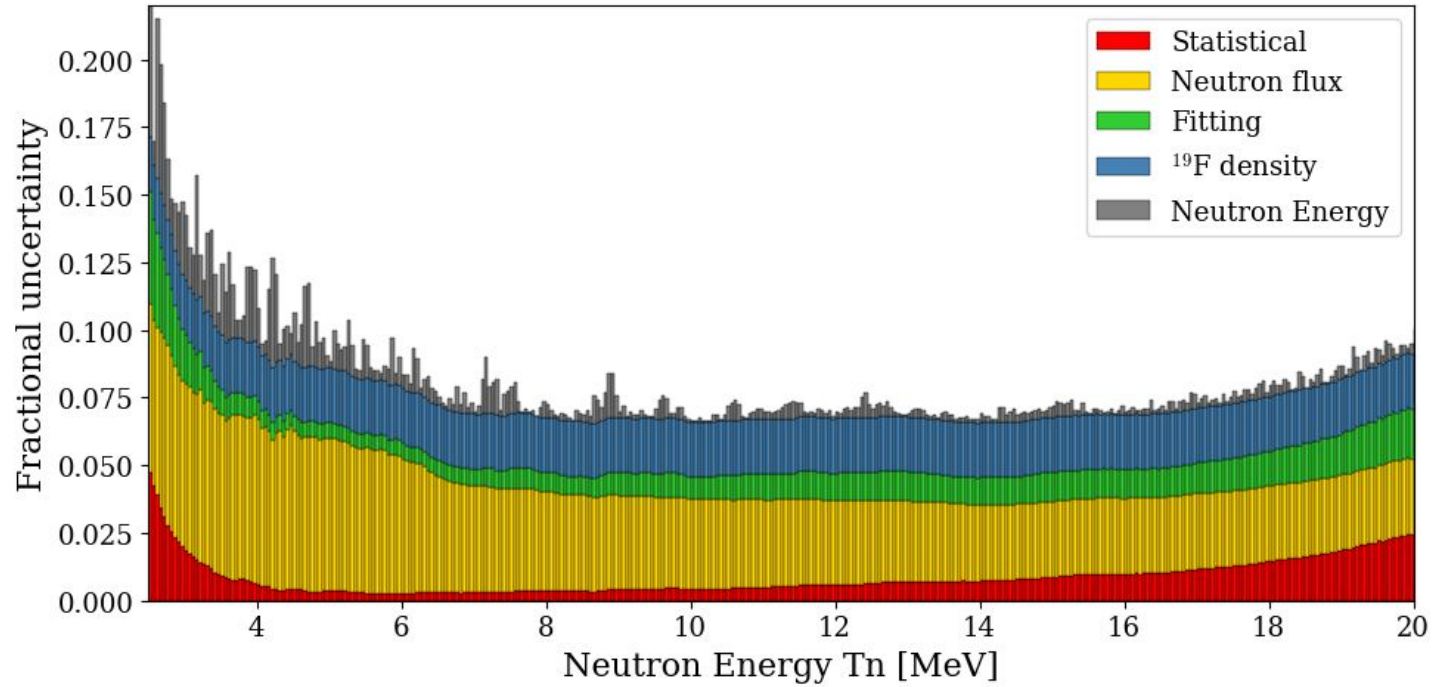
→ Data contamination

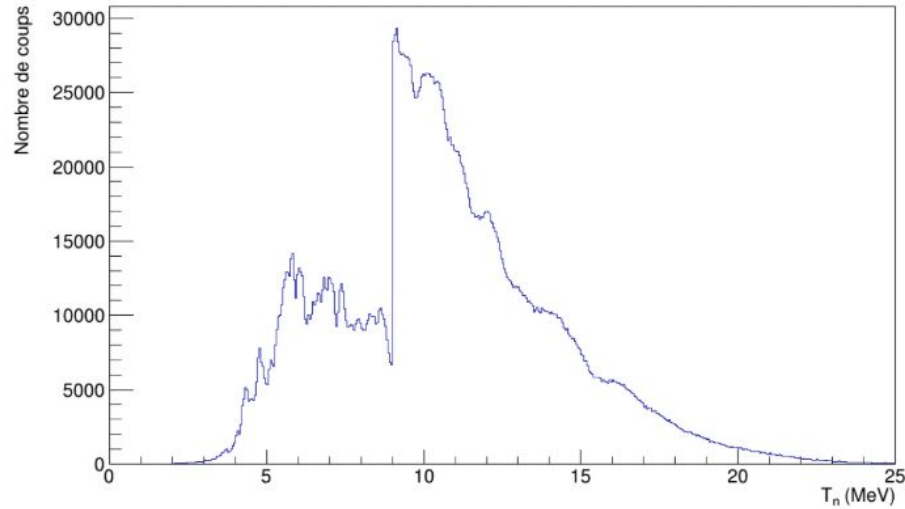
- hydrogenated materials in the IC chathode
- **60% of the statistic lost** (prohibitive for $^{16}\text{O}(n,\alpha)^{13}\text{C}$)

→ Cross section **normalization**

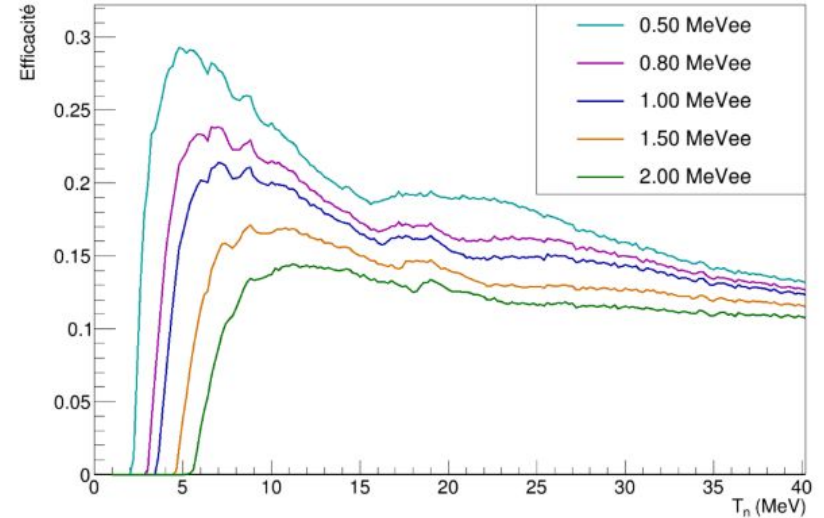
- normalization of the data by the neutron flux
- use of different beam monitors : LS/MM, U8 FC [10]

→ **SCALP** modifications and improvement of the normalization procedure at NFS (SPIRAL2, GANIL)

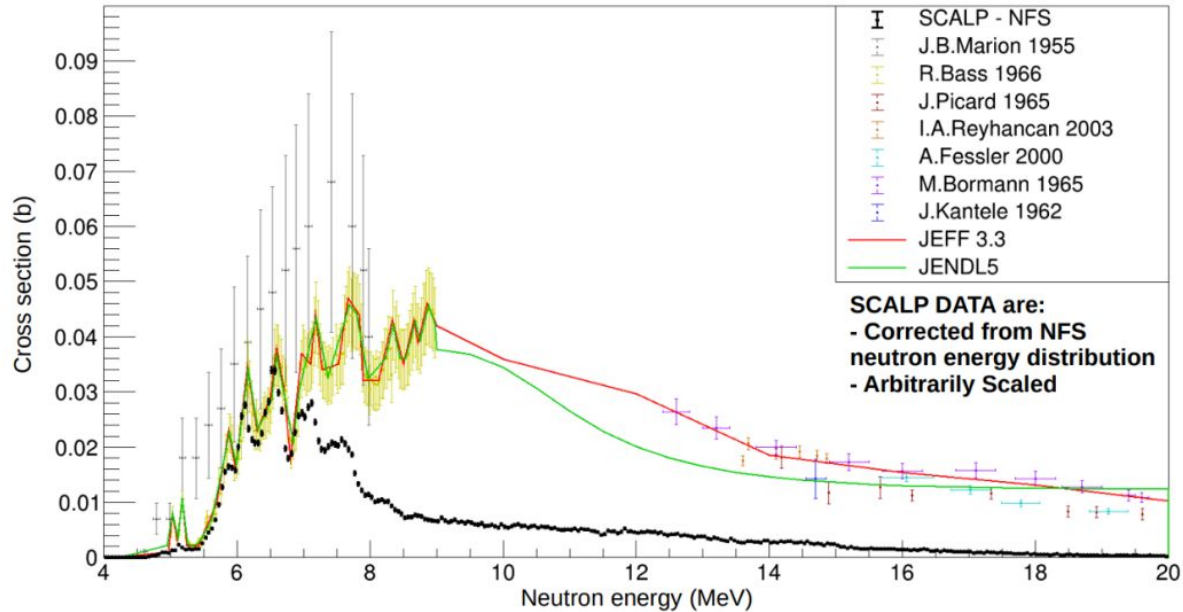




- Detected (n,a) events on ^{19}F
- p(n,n)p contamination cut off



- Liquid scintillator + Micromegas
- Unknown efficiency
- U8-FC was not part of the setup



→ Accessible in the Identification Matrix

→ from threshold up to 8 MeV (then other reaction channels dominate)

- $p(n,n)p$ as reference (IAEA standard) for flux measurement
- dE-dE-E telescope for PID at $[0;45]^\circ$ recoil angles

