Neutron detectors for new physics opportunities

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Why do we need neutron detectors?

- In nuclear structure, for β-decay studies and as ancillary detectors for powerful in-beam γ–ray spectroscopy arrays. Very important data for nuclear astrophysics and for technological applications.

- In nuclear reactions, for understanding the reaction mechanisms (improving reaction theory) or for the identification of the reaction channels (ancillary).

- Applications:

  - In nuclear medicine and radioprotection, as radiation monitors and dosimeters.
  - In material science, for neutron imaging techniques.
  - In nuclear technologies and security applications, in-core detectors, identification of fissile materials and cargo inspection.
  - In oil industry, for the well logging.

β-delayed neutron emission

Beta decay of neutron-rich nuclei:

For $S_n < E_x < Q_\beta$ typically
$\Gamma_n(E_x) >> \Gamma_\gamma(E_x)$

- Far enough from stability $S_{xn} < Q_\beta$: multiple neutron emission

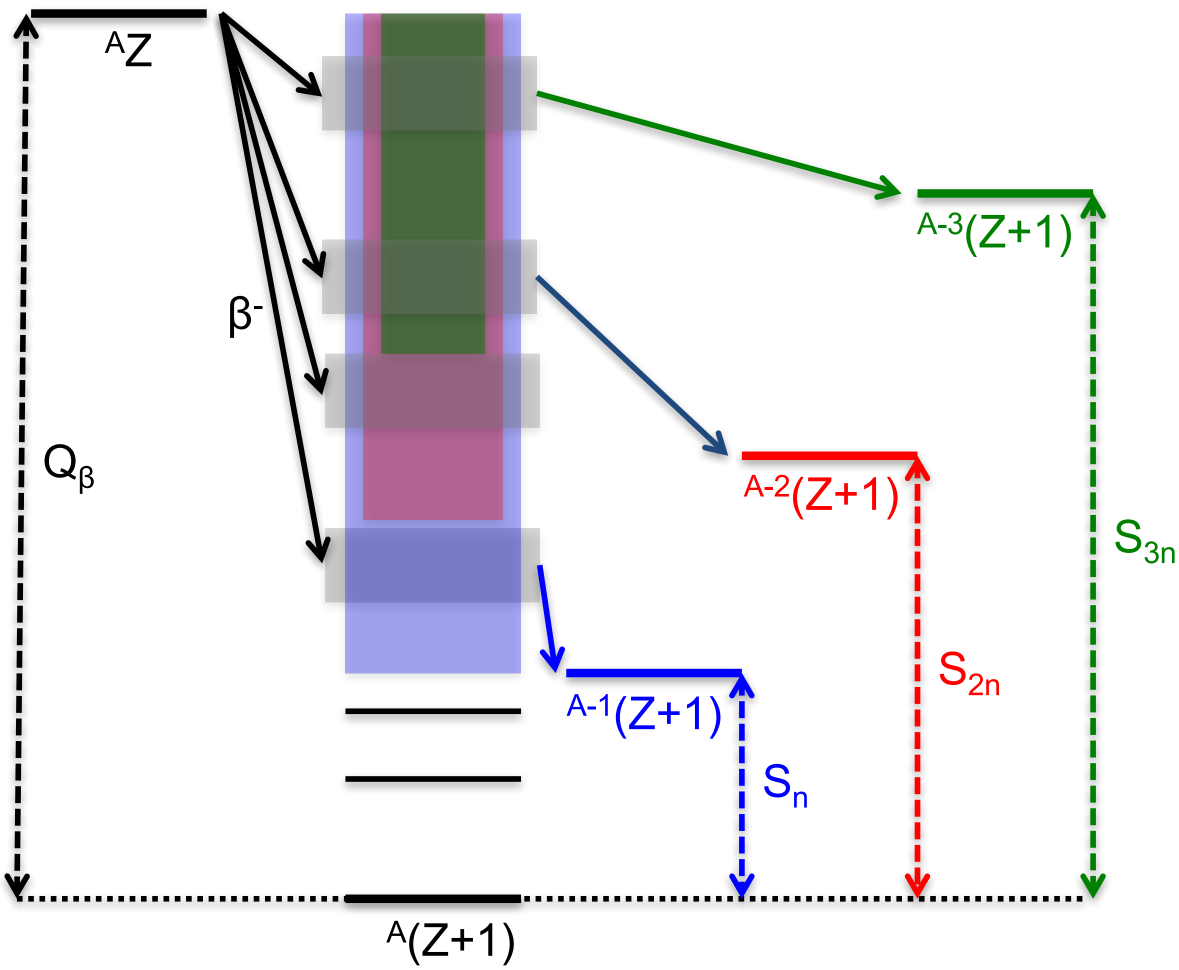
Physical quantities:

Delayed neutrons **$E_n \leq 10$ MeV**

Measure E_n, I_β, J_π

Possible **β-2n, β-3n** for large **Q_β**

n-n correlations: sequential/direct



Not an easy task!

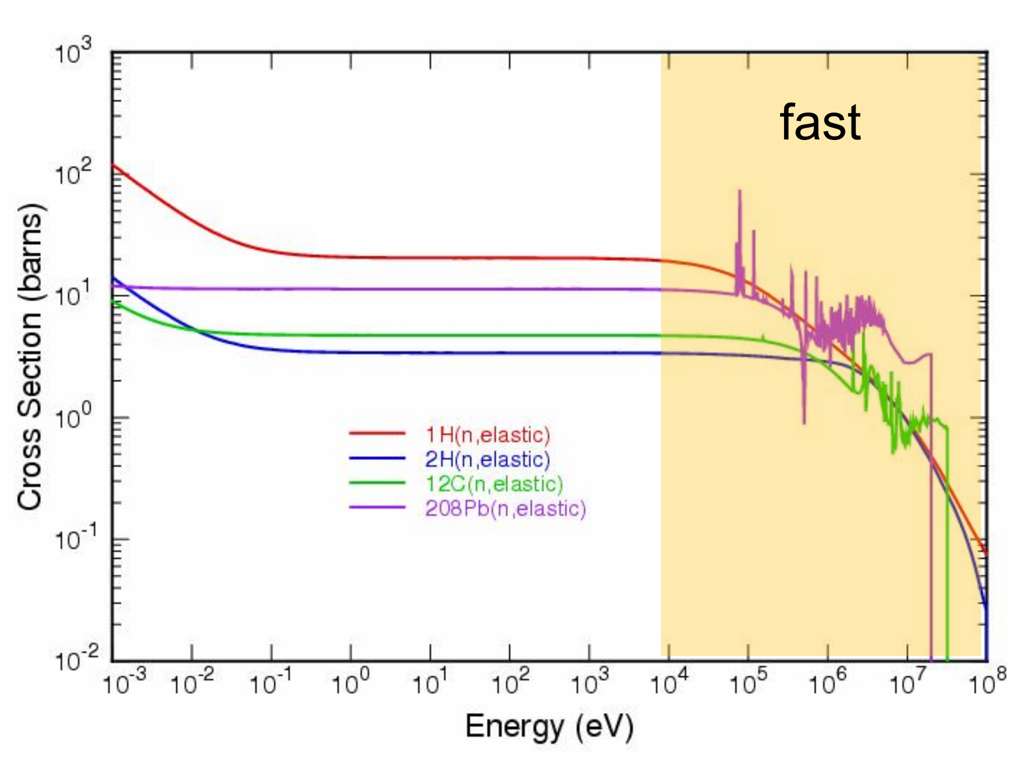
Common nuclear reactions used in neutron detectors

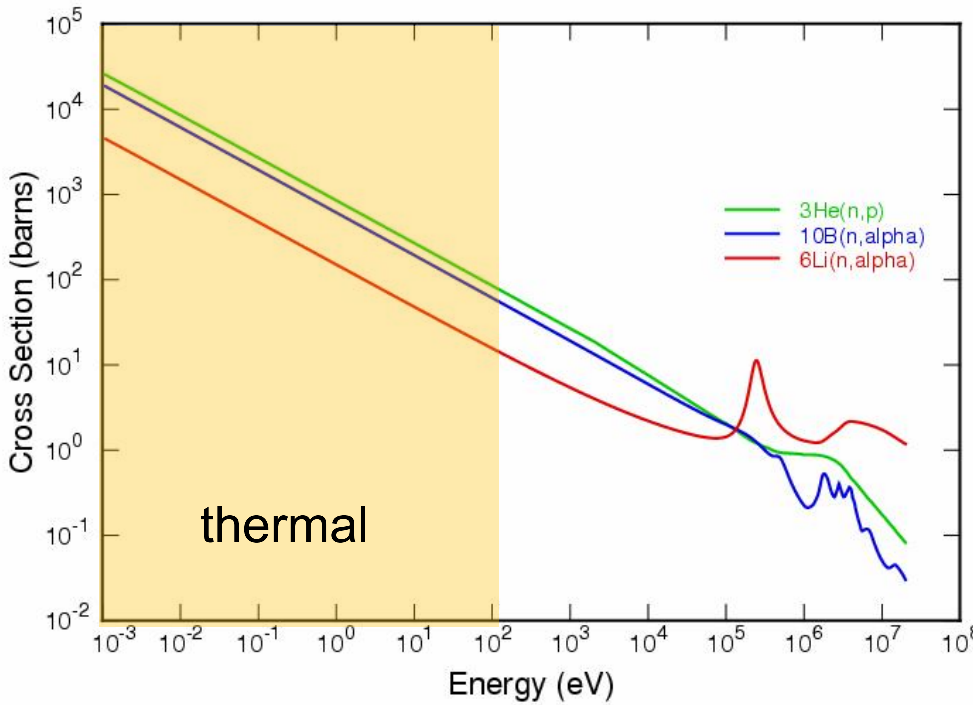
(n,n)

n + ^{1}H $\rightarrow$ n + ^{1}H
n + ^{2}H $\rightarrow$ n + ^{2}H

(n,ch.p.)

n + ^{3}He $\rightarrow$ ^{3}H + ^{1}H + 0.764 MeV
n + ^{6}Li $\rightarrow$ ^{4}He + ^{3}H + 4.79 MeV
n + ^{10}B $\rightarrow$ ^{7}Li* + ^{4}He$\rightarrow$ ^{7}Li + ^{4}He + γ
0.48 MeV + 2.3 MeV





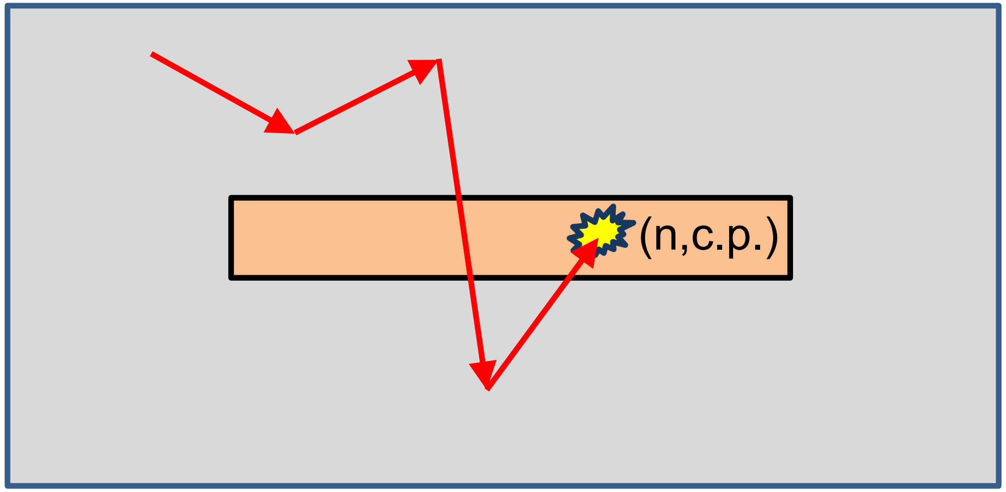
(n,ch.p.)(sensitive to thermal neutrons)

n + **^{3}He** $\rightarrow$ $^{3}H + {}^{1}H$ + 0.764 MeV
n + **^{6}Li** $\rightarrow$ $^{4}He + {}^{3}H$ + 4.79 MeV
n + ^{10}B $\rightarrow$ $^{7}Li^{*} + {}^{4}He \rightarrow {}^{7}Li + {}^{4}He + \gamma$ 0.48 MeV +2.3 MeV

Gaseous detectors: **^{3}He**, BF_3
^{6}Li-doped detectors: **Li-glass**

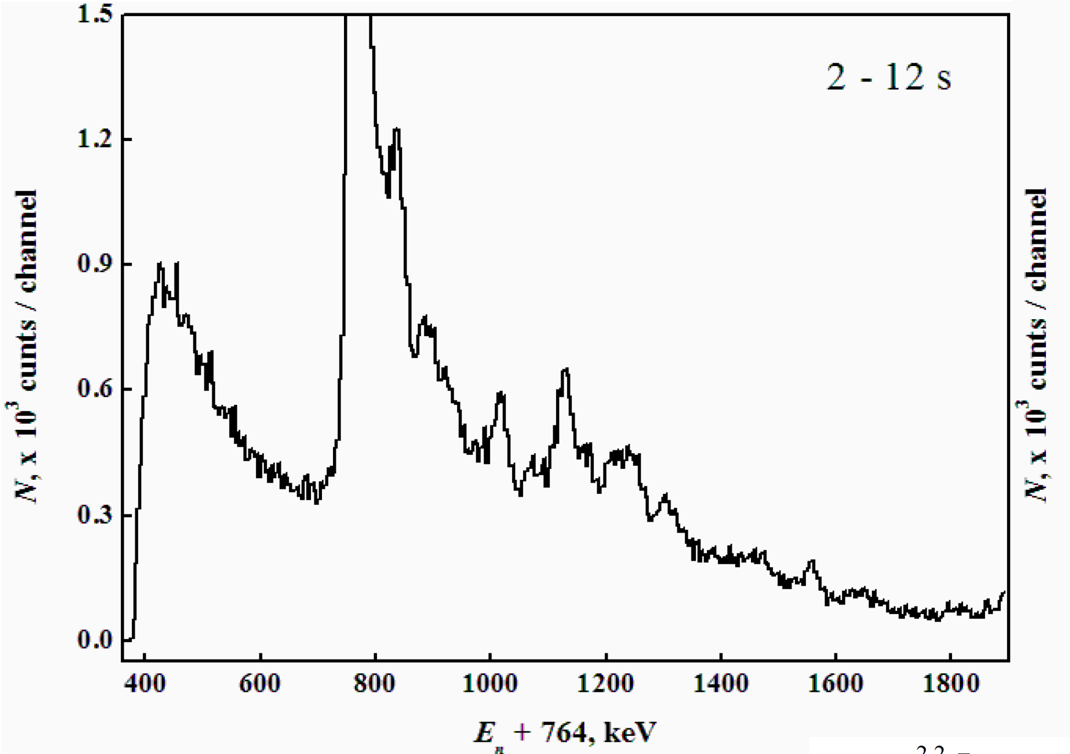
Bare detector (^{3}He, ^{6}Li)

- High efficiency at thermal energies.
- Possible spectroscopy in the keV range (low efficiency). The signal is proportional to the E_n.

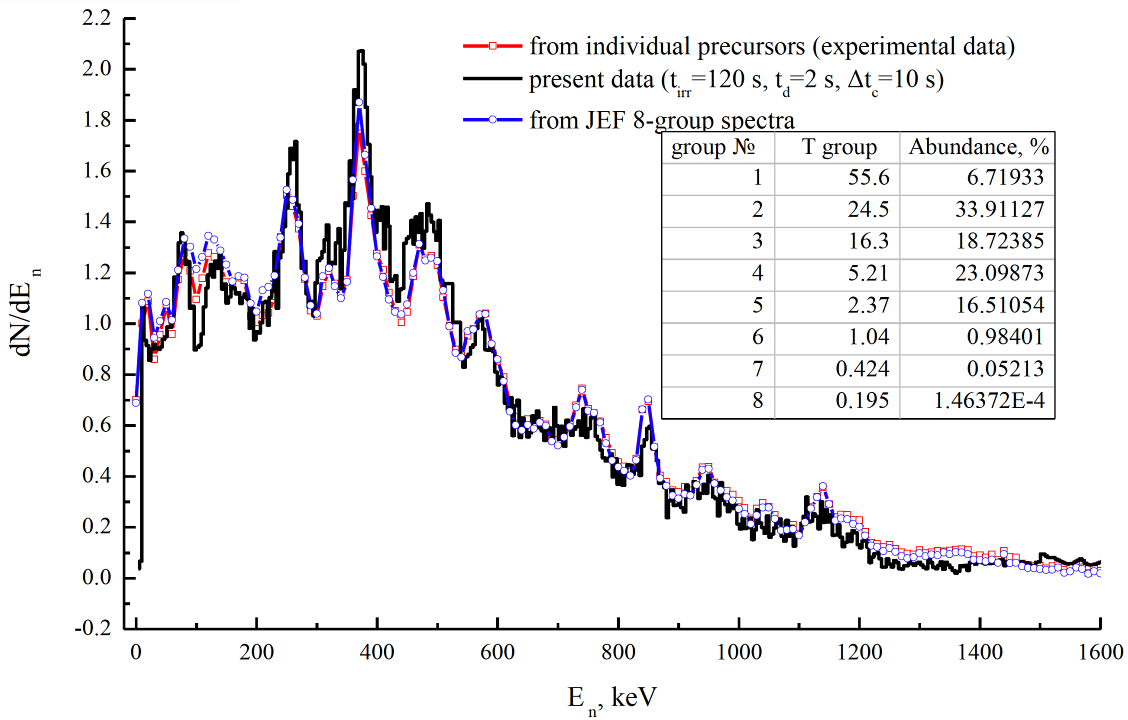


Detector (^{3}He, BF_3) surrounded with moderator (polyethylene)

- High efficiency at all E_n. Can be independent on the E_n with an adequate design (**long counters**).
- Large moderation times (~1 ms)
- The information of the incident E_n is lost.



De-convolution



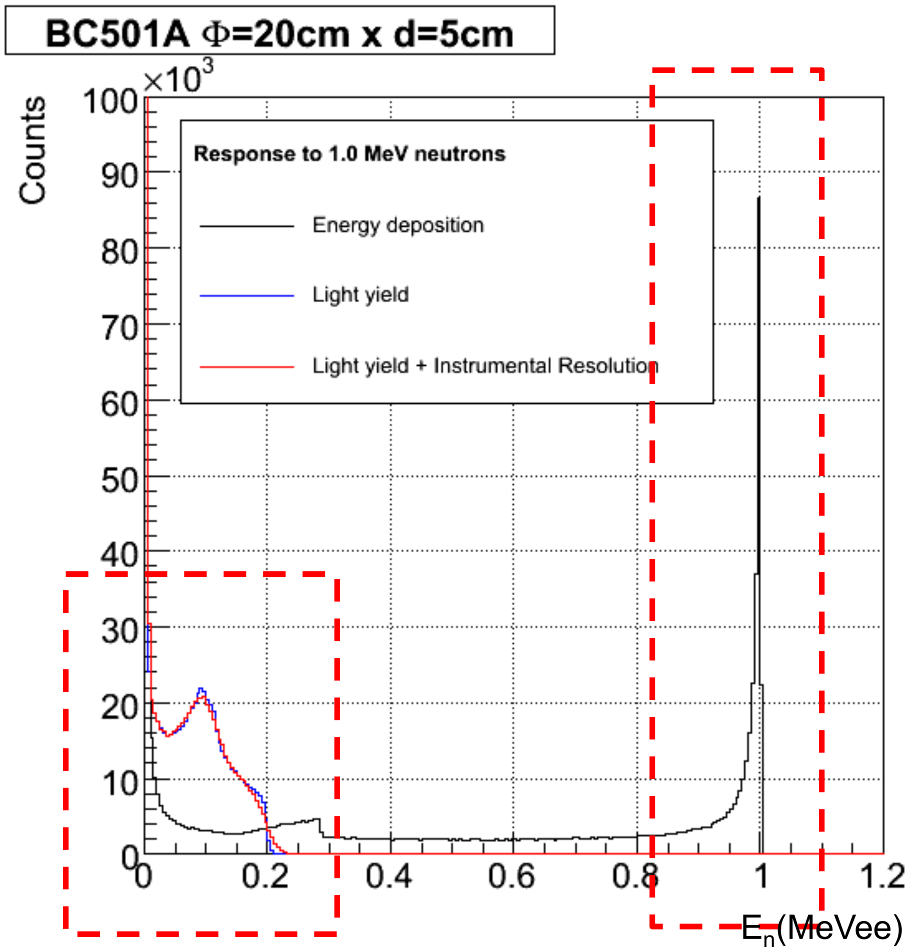
group №	T group	Abundance, %
1	55.6	6.71933
2	24.5	33.91127
3	16.3	18.72385
4	5.21	23.09873
5	2.37	16.51054
6	1.04	0.98401
7	0.424	0.05213
8	0.195	1.46372E-4

β-delayed neutron pulse height spectra from $^{235}U(n,f)$ fission fragments measured with an array of bare ^3He detectors.

V. M. Piksaikin et al. - Coordinated Research Project on the Development of a Reference Database for beta-delayed neutron emission, IAEA, Vienna, Austria

Elastic scattering (E_n > 100 keV)

n + **^{1}H** → n + ^{1}H
n + ^{2}H → n + ^{2}H



Solid organic crystals: Stilbene, Anthracene…
- Toxic, anisotropic light production, non proportional light yield

Plastic scintillators: BC400…
- Easy to shape and handle, no (good) pulse shape n/γ separation.

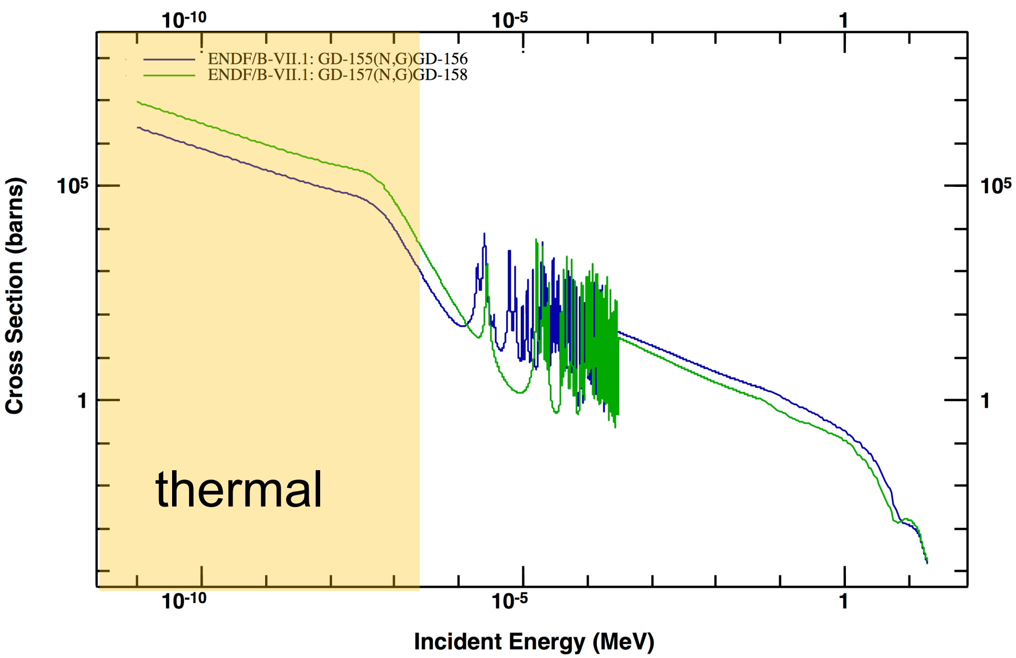
Liquid scintillators: NE213/BC501A/EJ301, EJ309, BC537…
Highly flammable, toxic (aromatic), **good pulse shape n/γ separation**

H(n,p) - plastic or liquid:
- High E_n threshold (> 100 keV).
- Poor energy resolution (~20% @ 1 MeVee).
- Signal not proportional to the incident E_n. Different light output for e- and heavy charged particles.
- Large volumes, high intrinsic efficiency.
- Fast response: **time of flight spectroscopy** (trigger with a β-detector).

Radiative capture

n + ^{155}Gd $\rightarrow$ ^{156}Gd* $\rightarrow$ γ-ray + CE spectrum

n + ^{157}Gd $\rightarrow$ ^{158}Gd* $\rightarrow$ γ-ray + CE spectrum



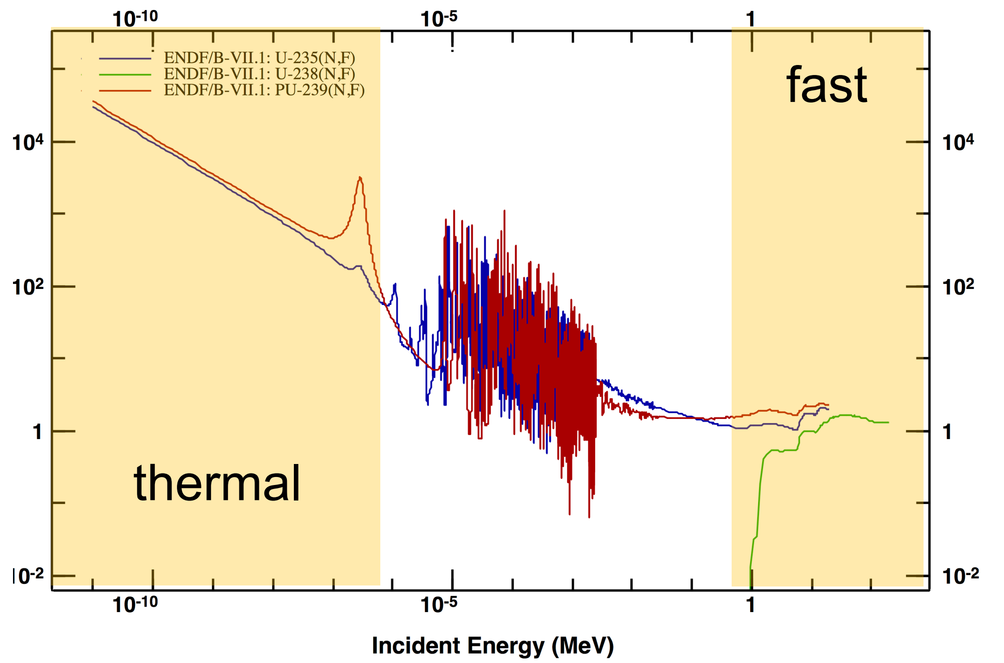
Fission

n + ^{235}U $\rightarrow$ fission fragments + ~160 MeV

n + ^{239}Pu $\rightarrow$ fission fragments + ~160 MeV

n + ^{238}U $\rightarrow$ fission fragments + ~160 MeV

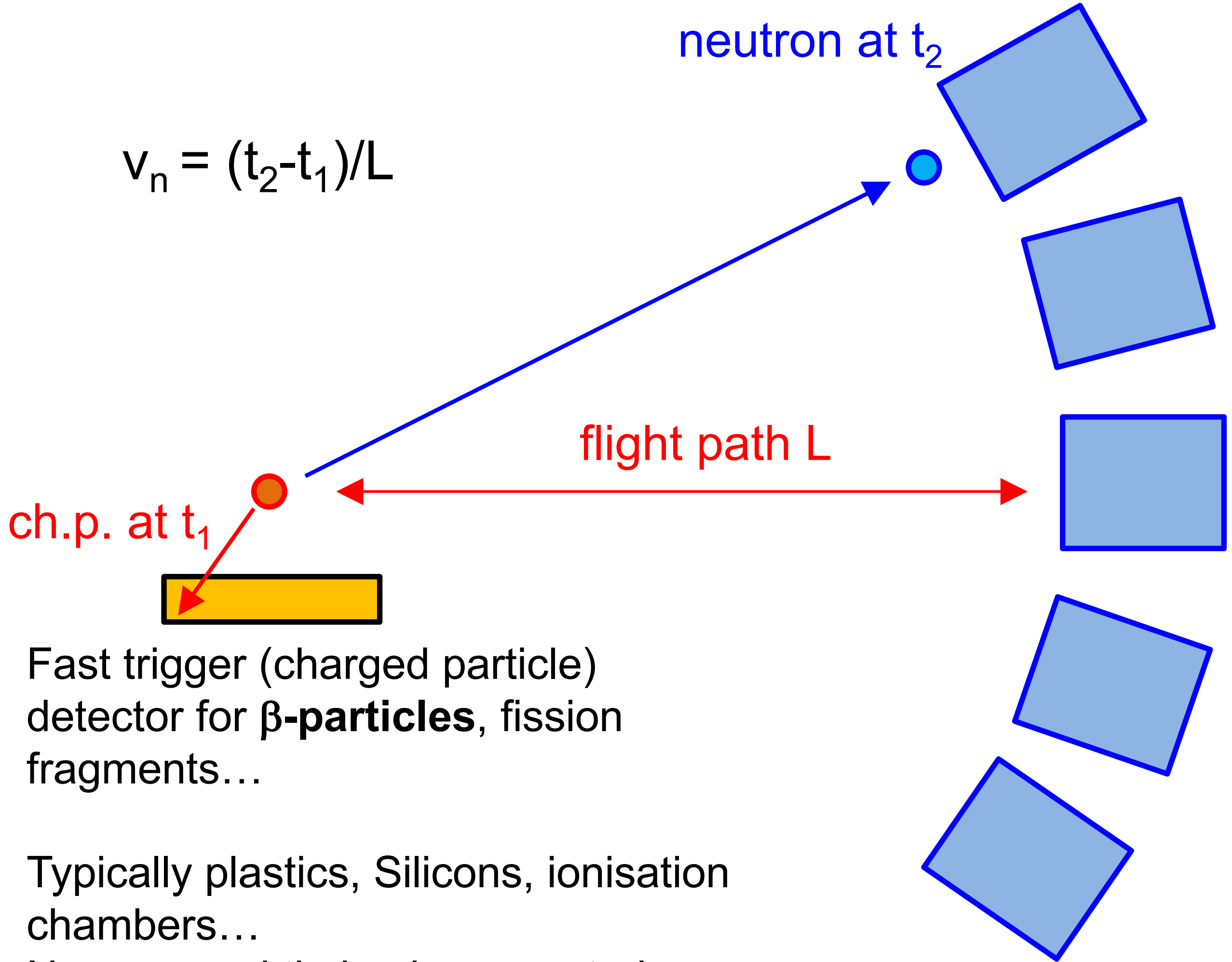
Very thin fissile targets (200 – 300 μg/cm^2) for detecting the fission fragments.



Time Of Flight (TOF) spectrometers

There has been a large number of neutron spectrometers worldwide built for different purposes: reaction studies, fission studies, decay spectroscopy…

$v_n = (t_2 - t_1)/L$



Fast neutron detectors (ns timing).

Compromise between the flight path, thickness and time resolution for getting a **high efficiency** and **good energy resolution**.

- **Low efficiency (<10%)**
- **Neutron spectroscopy**

Fast trigger (charged particle) detector for **β-particles**, fission fragments…

Typically plastics, Silicons, ionisation chambers…
Nanosecond timing is requested.

In the early 2000s: TONNERRE

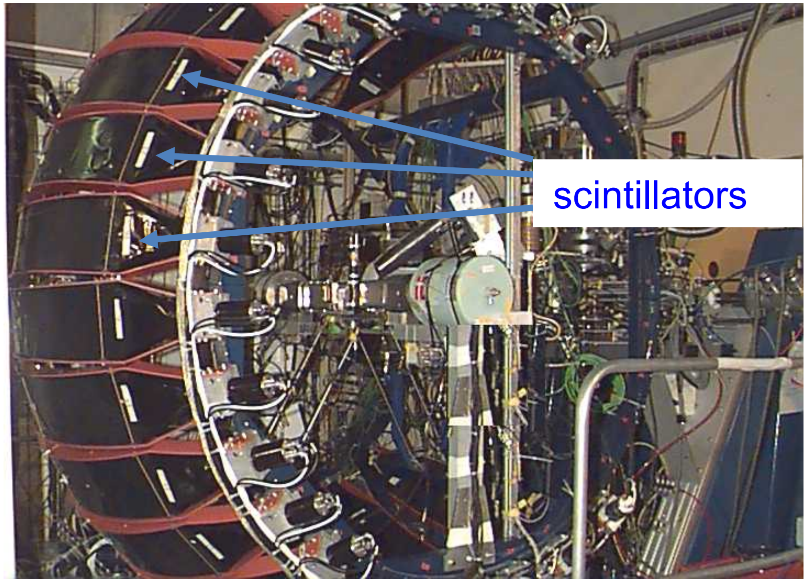
Up to 32 plastic scintillators [BC400, 160 x 20 x 4 cm, d=1.2 m]

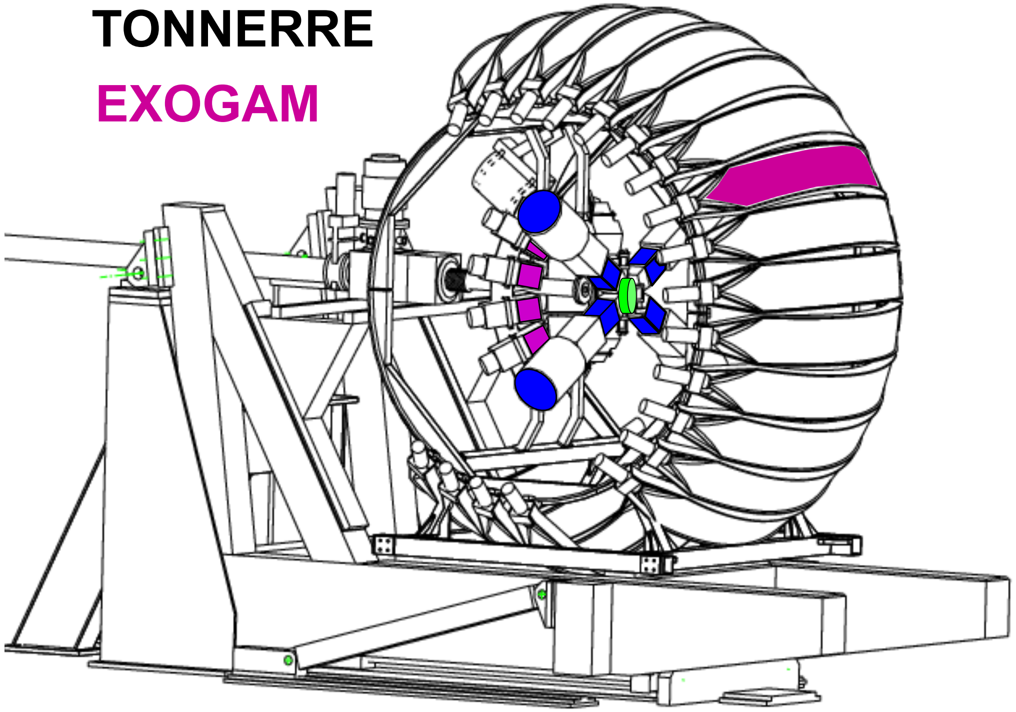
E_n by TOF : 200 keV < En < ~5 MeV

$\Delta\Omega \leq$ 45% of 4π

ΔE (1 MeV): ~ 80 keV

ε_n (1 MeV) ~ 50 %





A. Buta et al., NIM A455 (2000) 412

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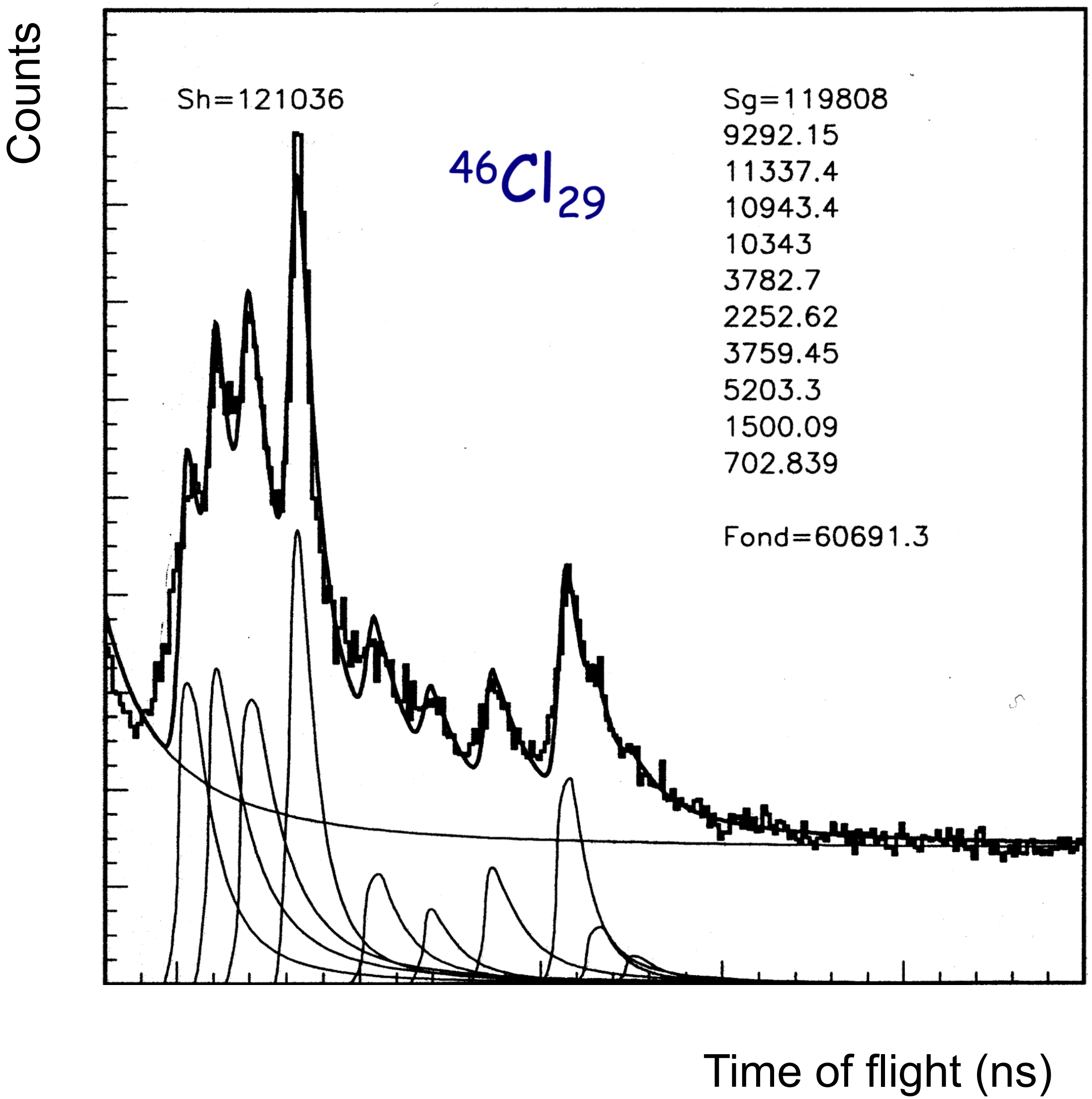
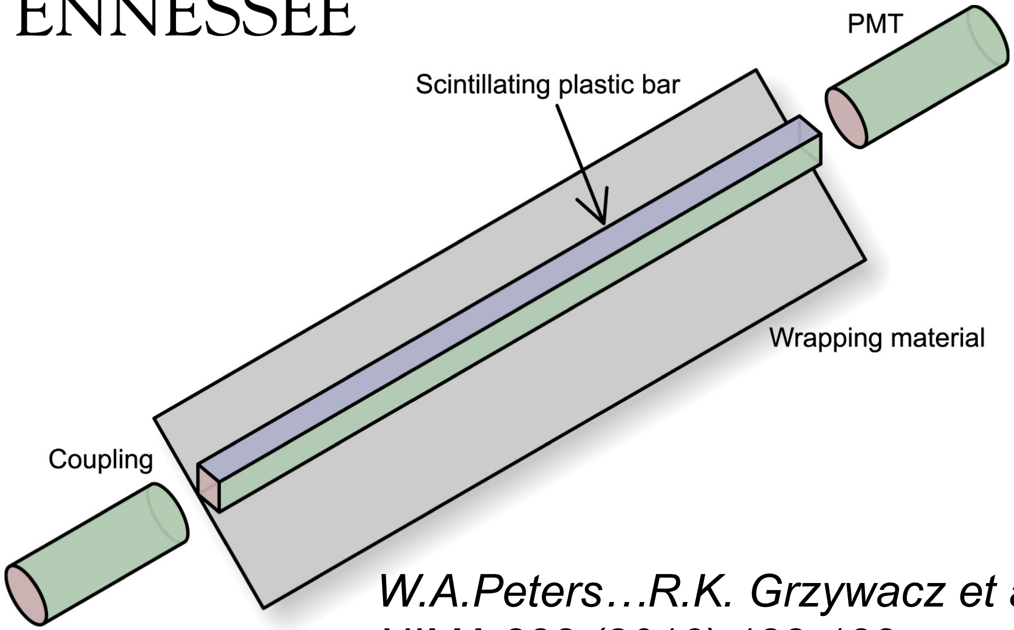


S. Grévy and the TONERRE collaboration

THE UNIVERSITY OF TENNESSEE

The VANDLE detector



W.A.Peters…R.K. Grzywacz et al.
NIMA 838 (2016) 122-133

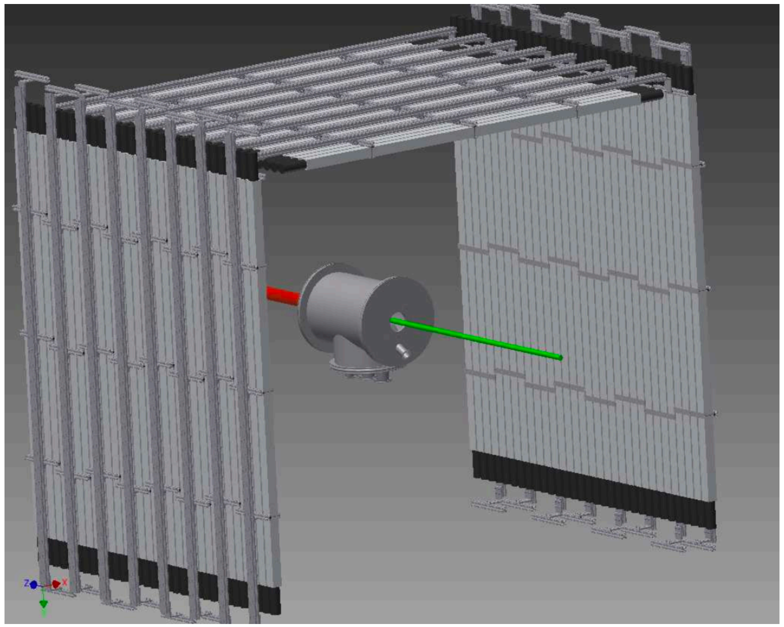
A highly modular array of plastic scintillators. Can be used to measure **β**-delayed neutrons and for reaction studies.

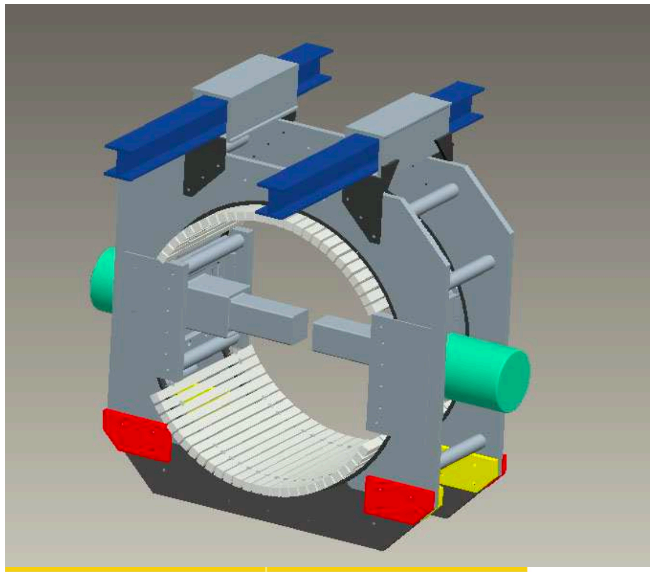
Plastic scintillator bar sizes:

- Small : 3x3x60 cm
- Medium : 3x6x120 cm
- Large : 5x5x200 cm

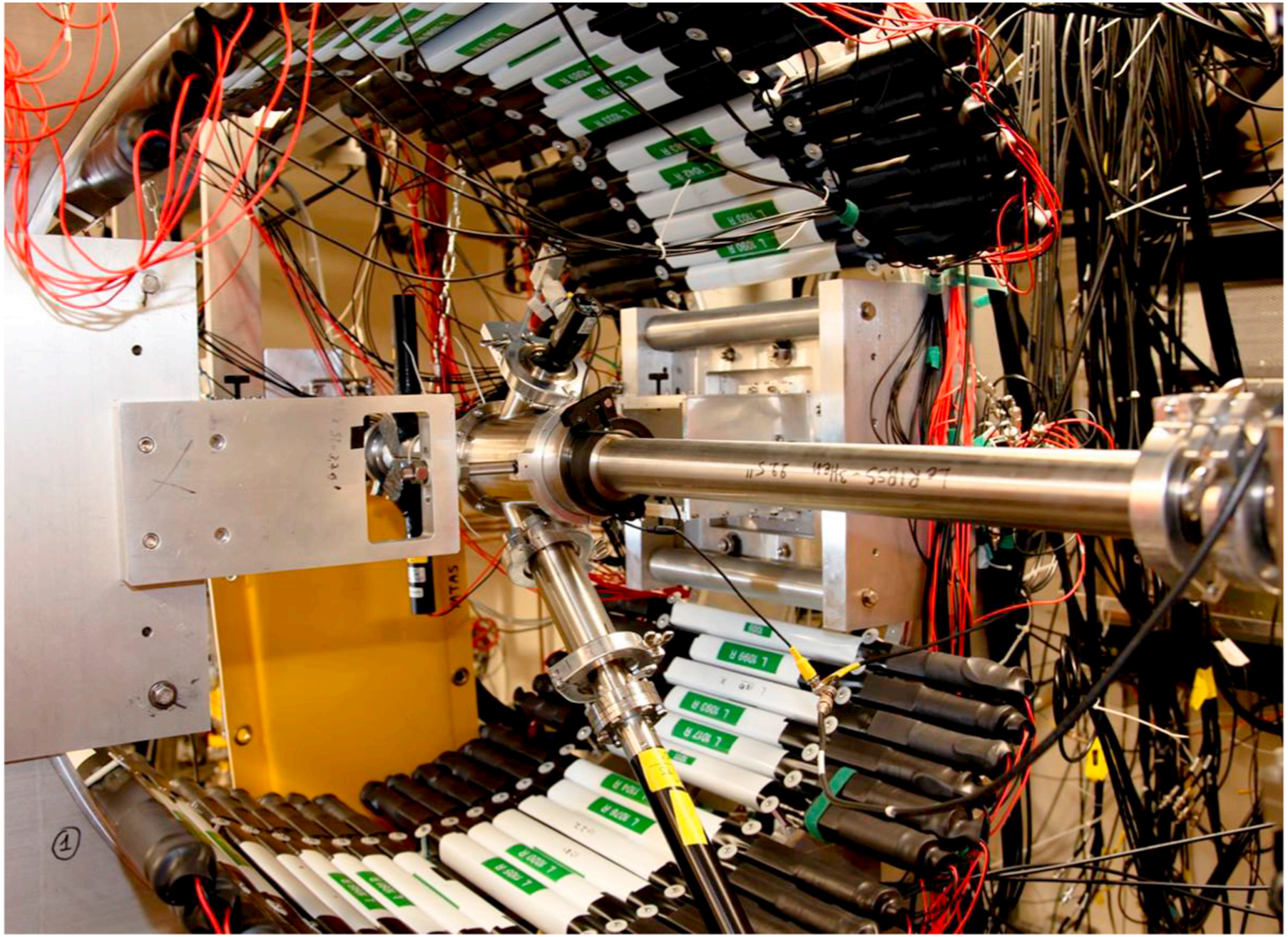
Neutron Energies Covered:

- Small/Med. : 0.1 - 3 MeV
- Large : 1 - 20 MeV





VANDLE at HRIBF



Other experiments planned/approved/made at ISOLDE Decay Station, RIKEN…

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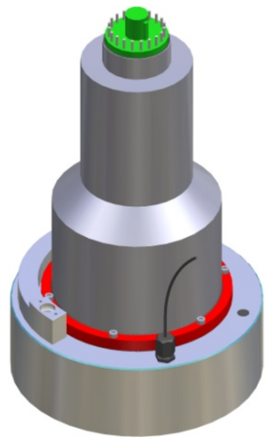
The MOdular Neutron SpectromeTER - MONSTER

- 100 cylindrical BC501A cell of 20 cm x 5 cm.
- Intrinsic efficiency (~50% @ 1MeV)
- Energy threshold E_n ~150 keV
- Good neutron timing ~1ns
- Digital DAQ 14bits & 1 Gsample/s

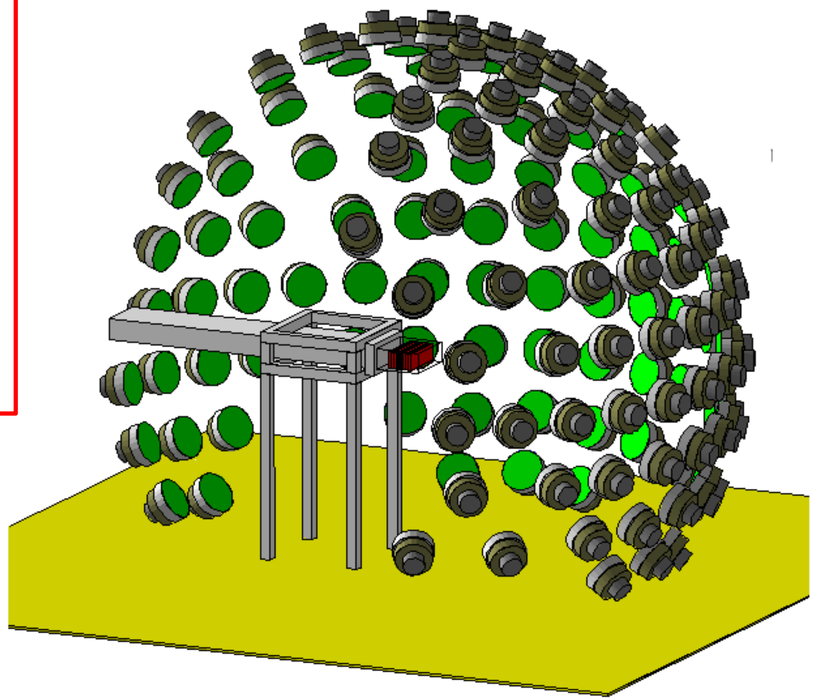


Ø=20cm x L=5cm

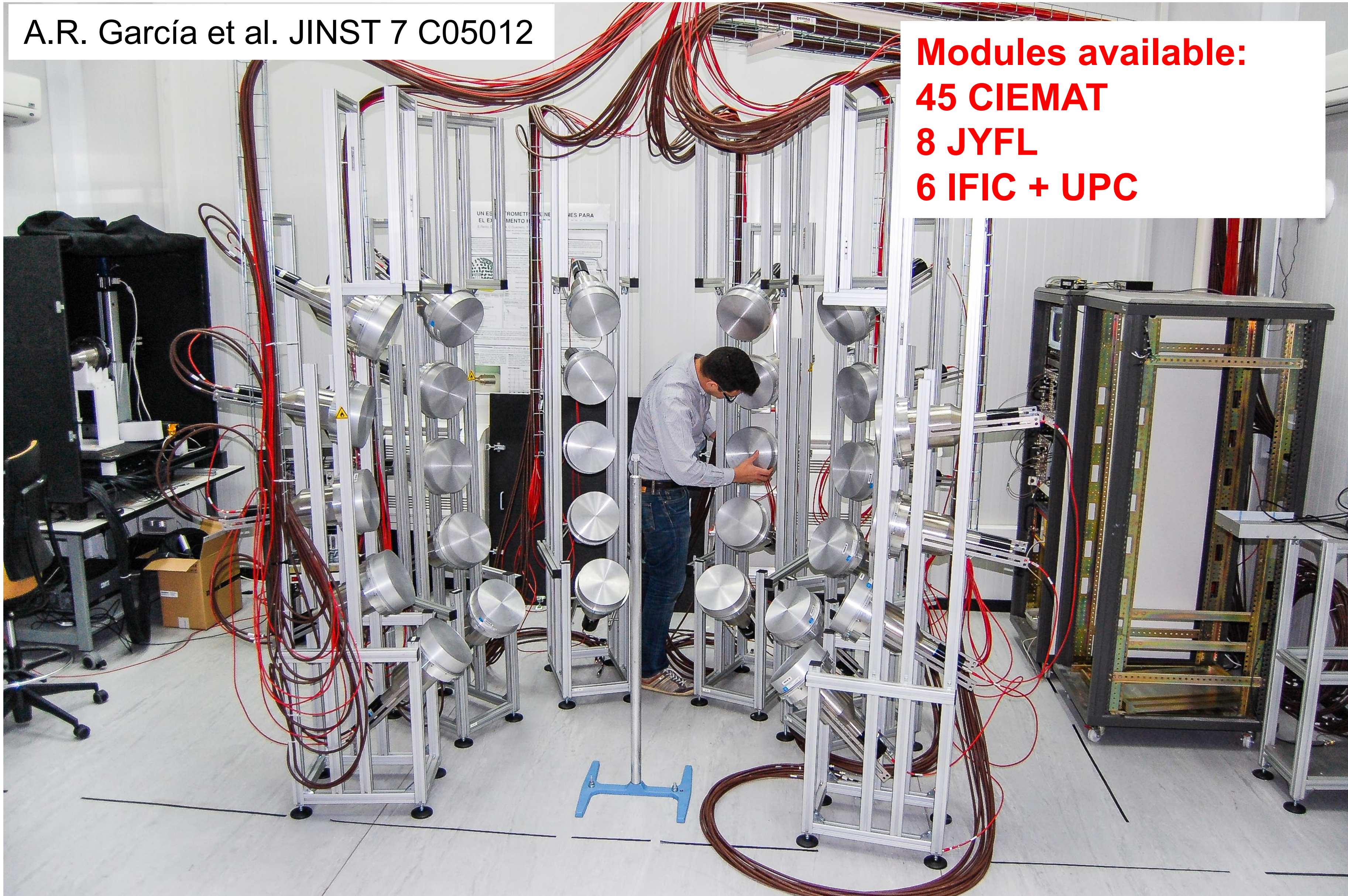
MOdular Neutron SpectromeTER (built for FAIR)

International collaboration:

CIEMAT, VECC (India), Univ. de Jyväskylä (Finlandia), IFIC (Valencia), UPC (Barcelona)



MONSTER



A.R. García et al. JINST 7 C05012

Modules available:
45 CIEMAT
8 JYFL
6 IFIC + UPC

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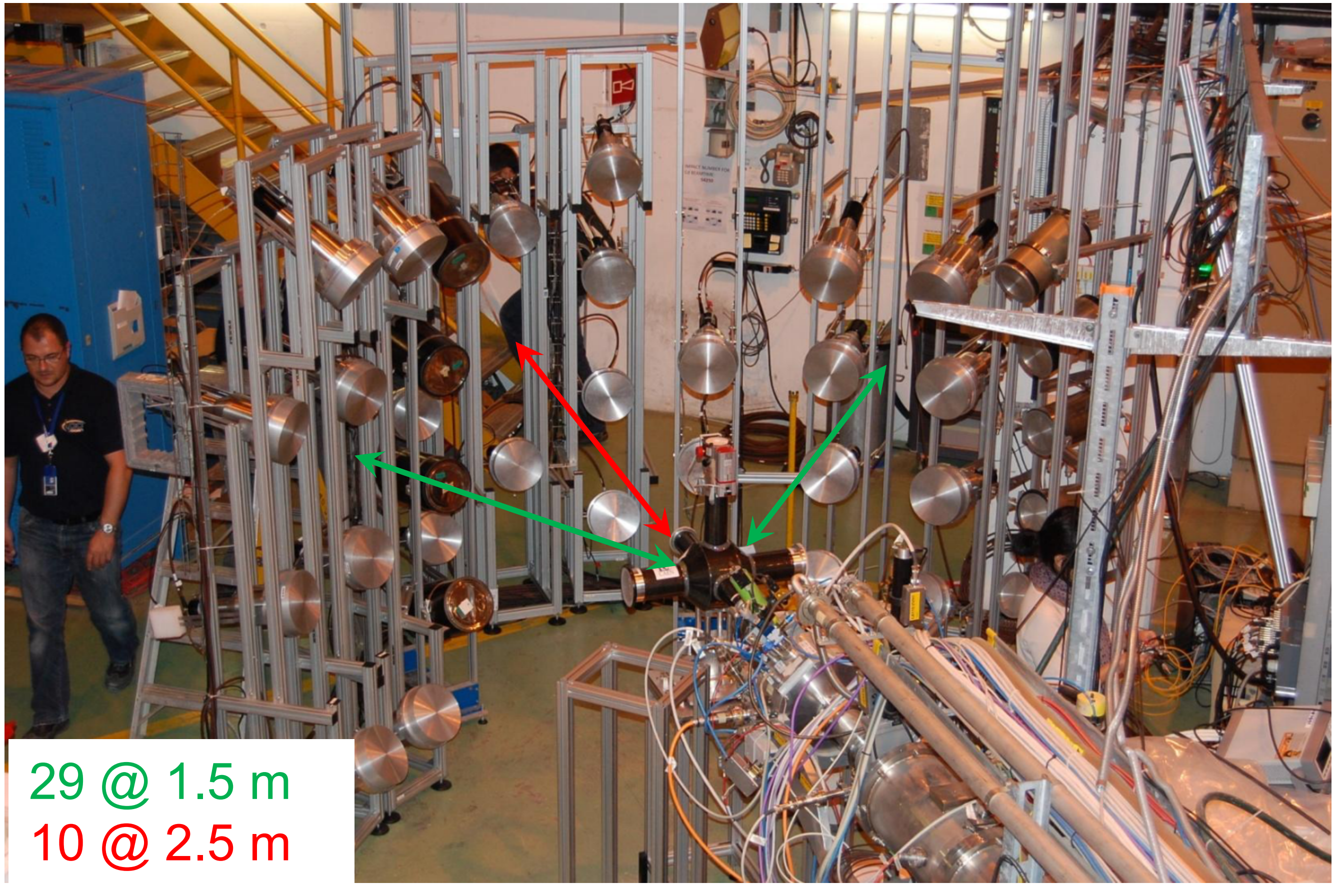
Pilot experiment IS525 @ ISOLDE



β-decay of ^{11}Li:
- Q_{β} = 20.6 MeV
- Weakly bound daughter ^{11}Be
- Variety of delayed particle emissions: 1n, 2n, 3n, n+α, t,d...

P_{2n} 4.2%:
- 2-neutron kinematics

Delayed 1-neutron emission still unclear:
- Unresolved weak transitions, uncertain branching ratios

Collaboration: <u>LPC Caen</u>, CIEMAT Madrid, UCM Madrid, Aarhus University, ISOLDE CERN, CSIC IEM Madrid, VECC Kolkata, CEA/SPhN Saclay, Univ. Santiago de Compostela, IPN Orsay, IFIC Valencia.

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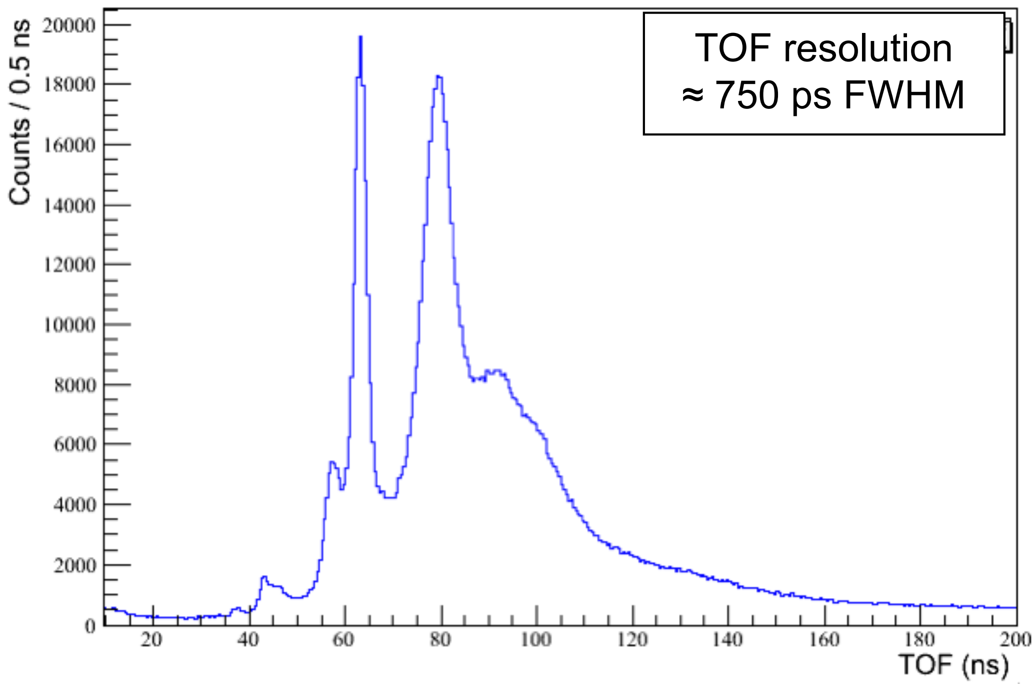
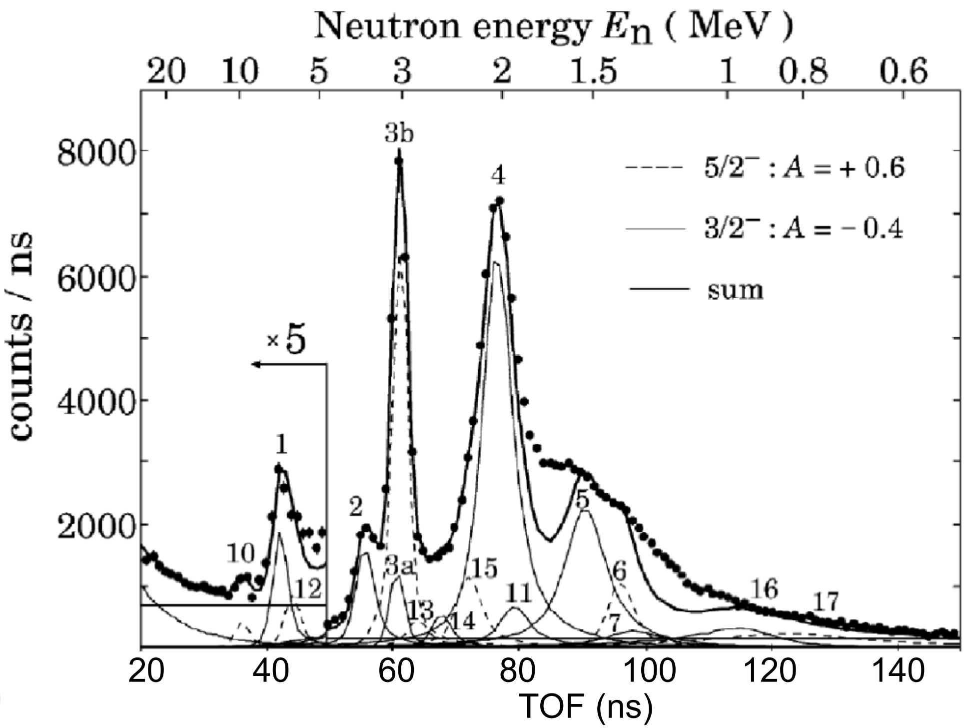
Preliminary results





Scientific program with MONSTER

- Test beams at FAIR Phase 0.
- Experiments approved at ALTO (β-decay of ^{83,83}Ga, ^{133}In) and NFS (prompt fission neutron spectra).
- Experiments planned at JYFL and at ISOLDE (under discussion with JYFL, UCM…).

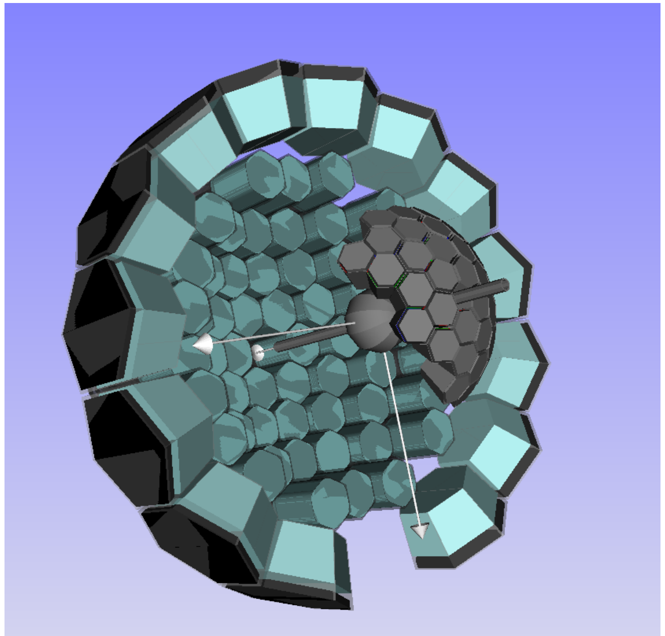
β-1n @ NEAR ARRAY

≈ 34 hours & n-γ discrimination

≈ 5 times Hirayama et al's statistics with similar E_n resolution* PLB 611(2005) 239

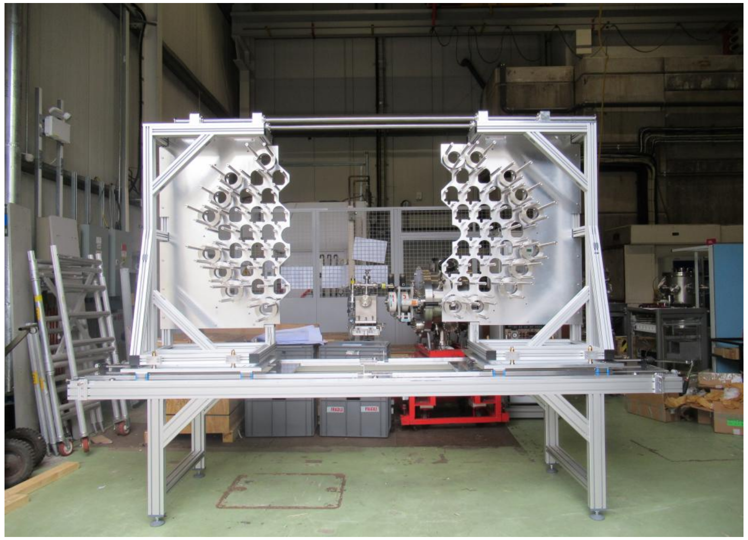
The NEDA array

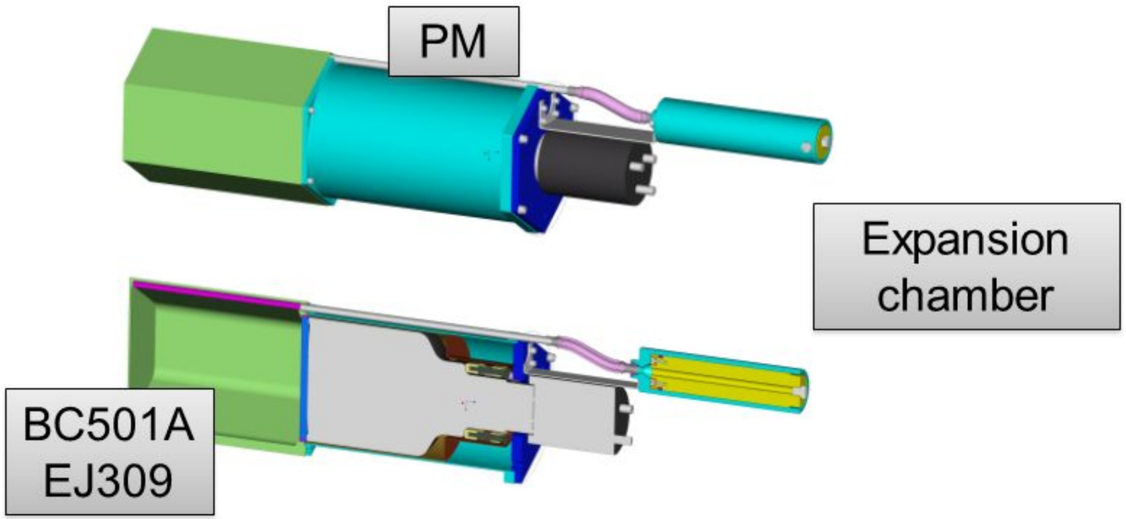
To be coupled to the AGATA γ-ray spectrometer as ancillary detector for in-beam studies.



Currently under construction.

- ~100 liquid scintillators (65 in 2018)
- Hexagonal prisms: 7 cm side x **20 cm thick**
- Very compact geometry and high intrinsic efficiency. Large cross talk between modules.
- Digital DAQ (same as AGATA).



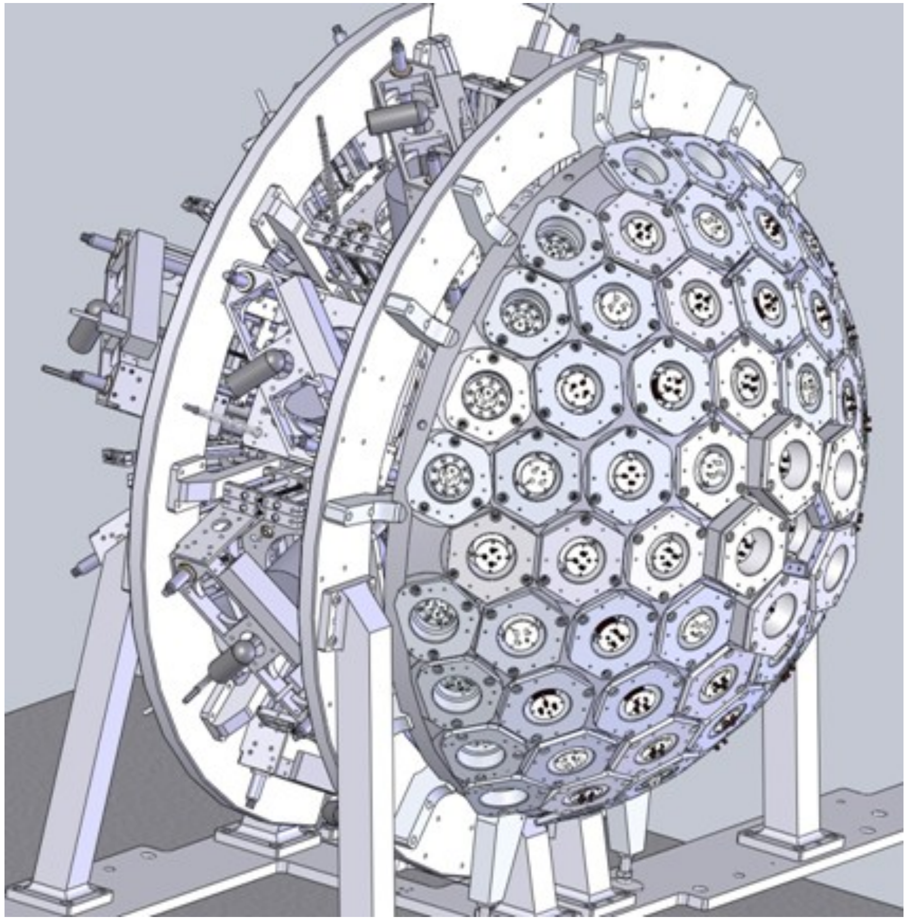


The deuterated scintillator DESCANT @ TRIUMF

UNIVERSITY of GUELPH

1.08 π deuterated scintillator (C_6D_6) BC 537/EJ315
100 keV – 10 MeV
15 cm thick detectors
12-bit & 1 Gsample/s
On board CFD, pulse heigh…

Small forward peak in the (n,d) reaction (?)
Worse threshold than BC501A.



P. Garret et al.

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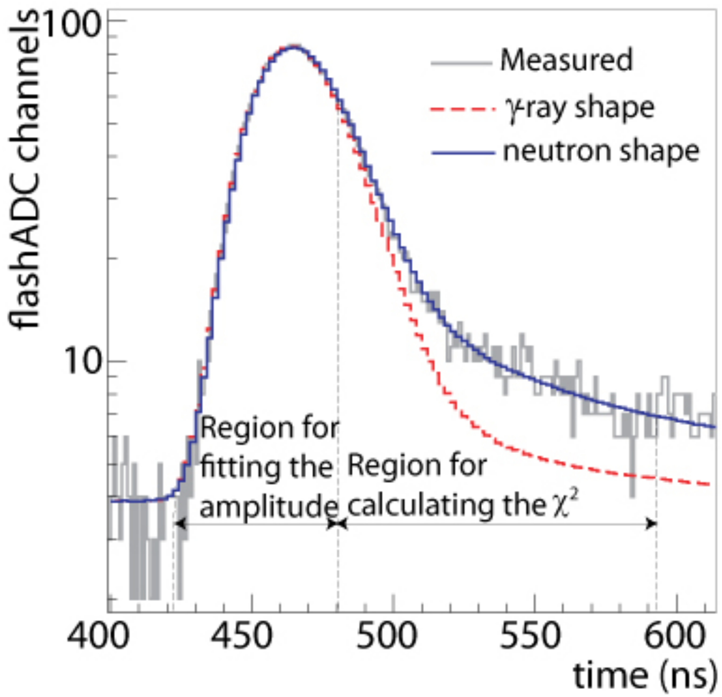
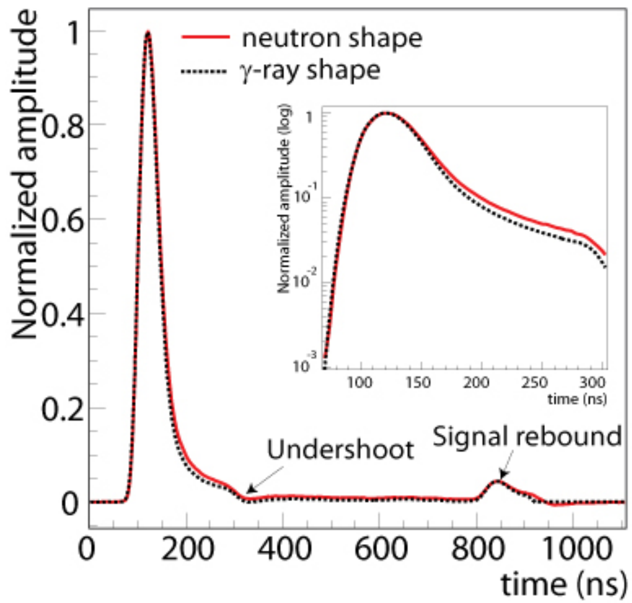
Digital data acquisition systems

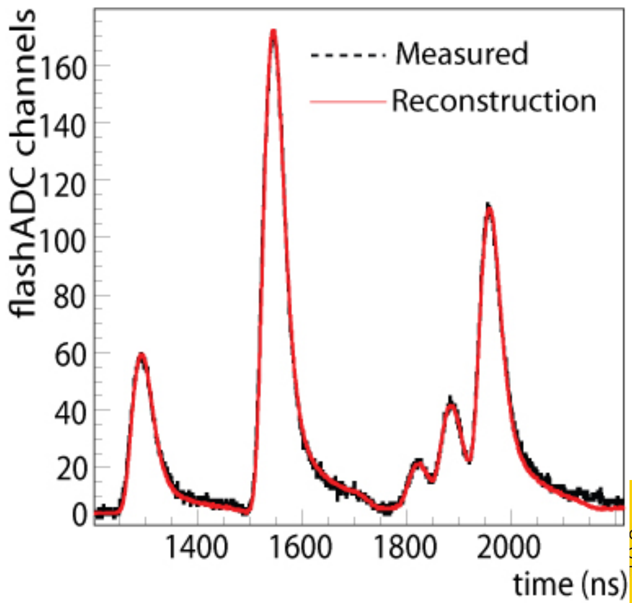
Systematic uncertainties <-> detector behavior

Digital DAQs allow to process in a very flexible way the detector signals.

Pulse shape analysis. Guerrero et al. NIMA 597(2008)212







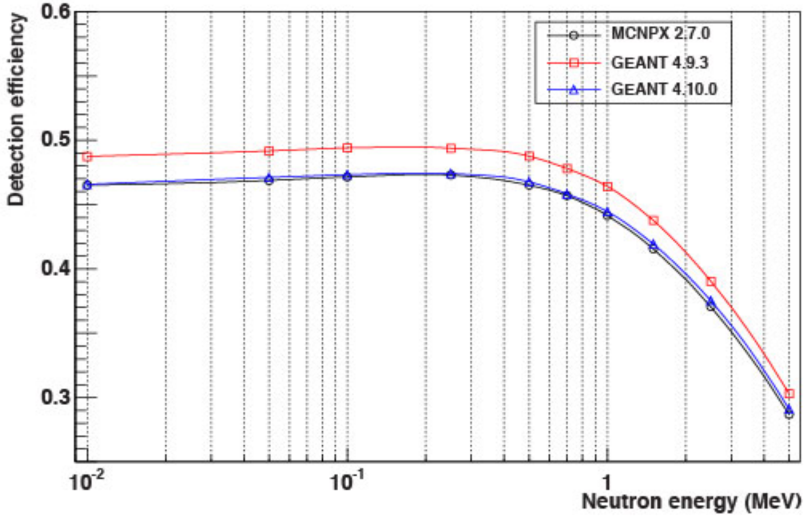
High efficiency "long counters"

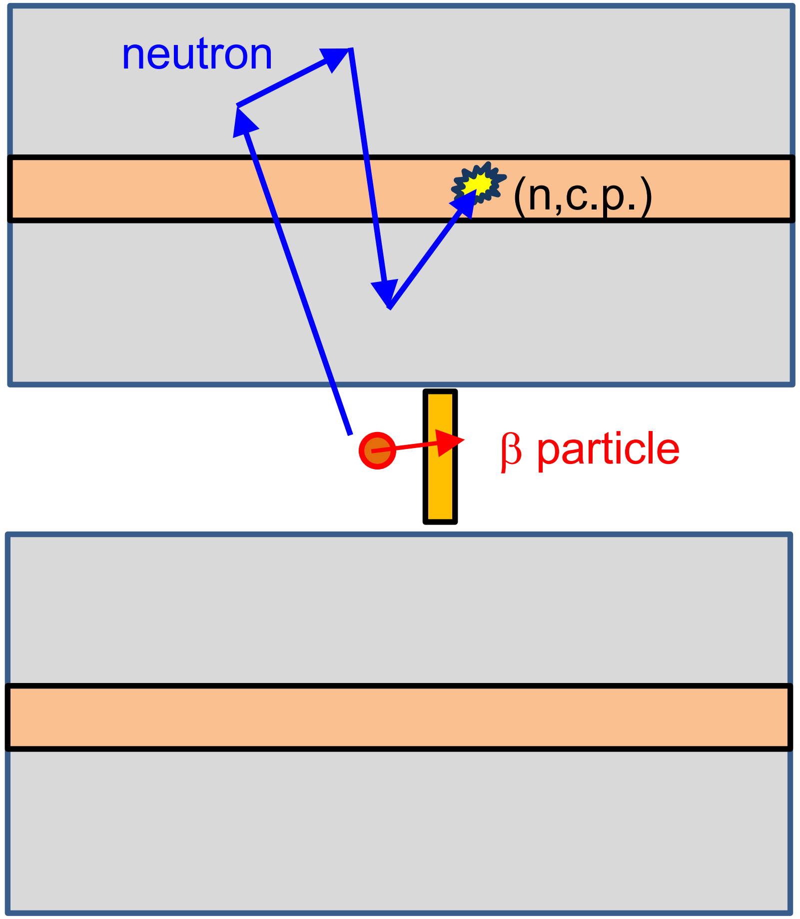
Measurement of the neutron emission probabilities P_n:

$$P_n = \frac{N_n}{N_\beta} = \frac{\epsilon_\beta}{\epsilon_n}\frac{N_n^D}{N_\beta^D}$$

N_n number of neutrons emitted
N^D number of particles detected, either neutrons or betas

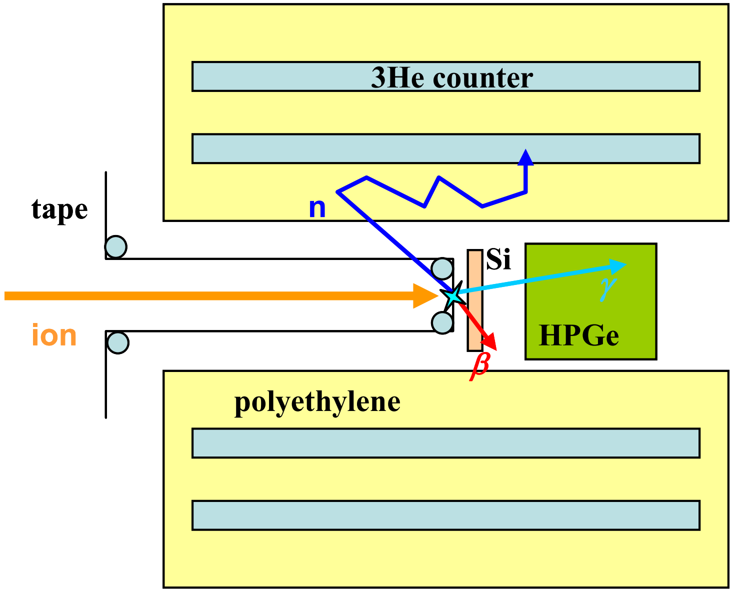
$\boldsymbol{\varepsilon_n}$ as independent as possible on the E_n.



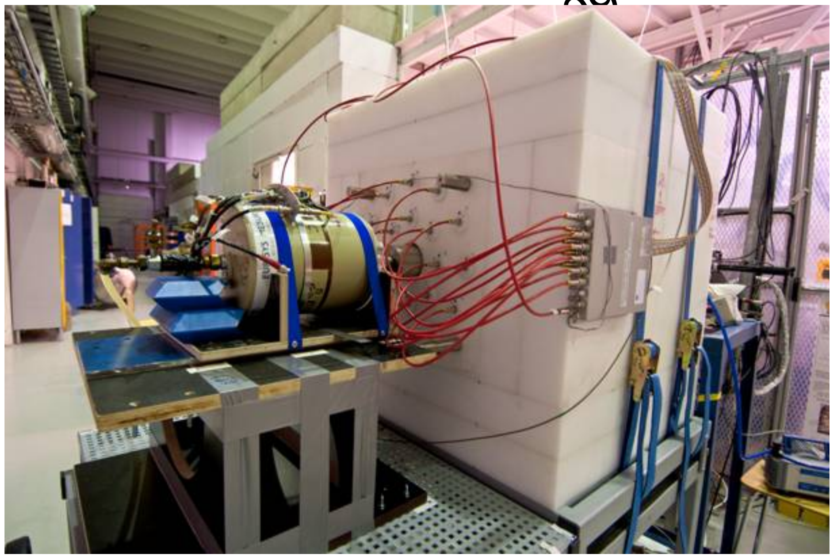


- **High efficiency (~70%)**
- **Neutron counting (no E_n)**

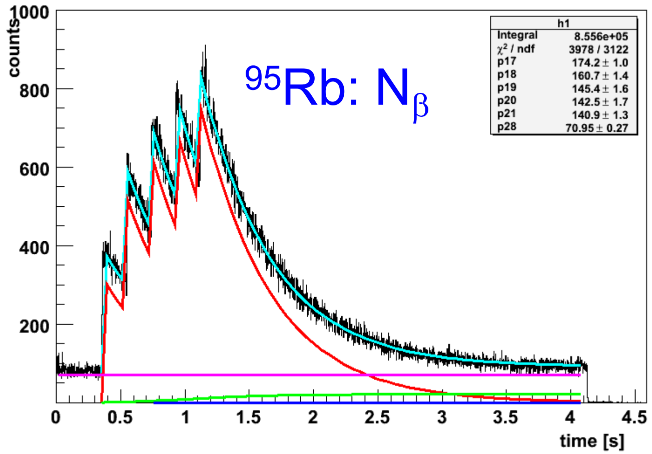
The BELEN-20 detector at Jyvaskyla: IGISOL+JYFLTRAP



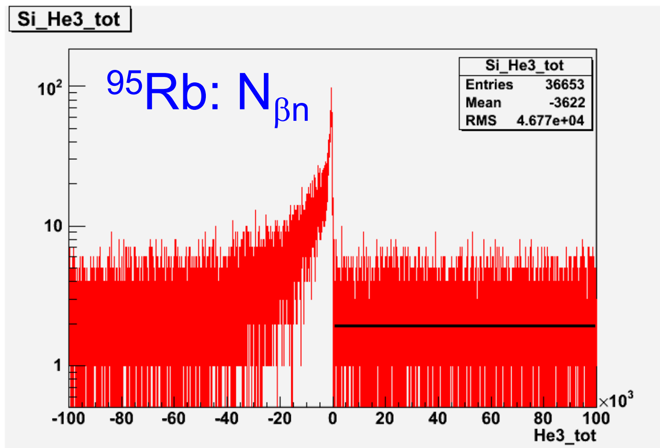
β-decay of isotopically pure beams!



Measurement of ^{88}Br, ^{94,95}Rb, ^{138}I, ^{138}Te…



β-rate along the time cycle



β-n time correlations

IFIC INSTITUT DE FÍSICA CORPUSCULAR

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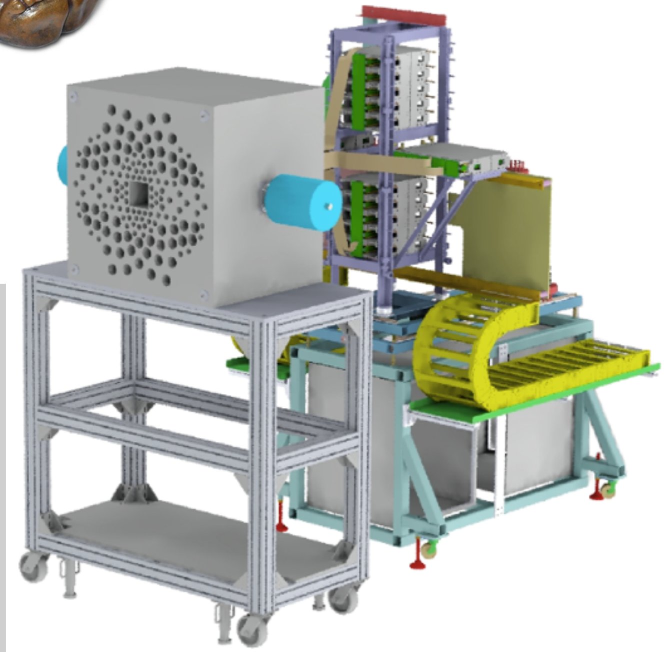
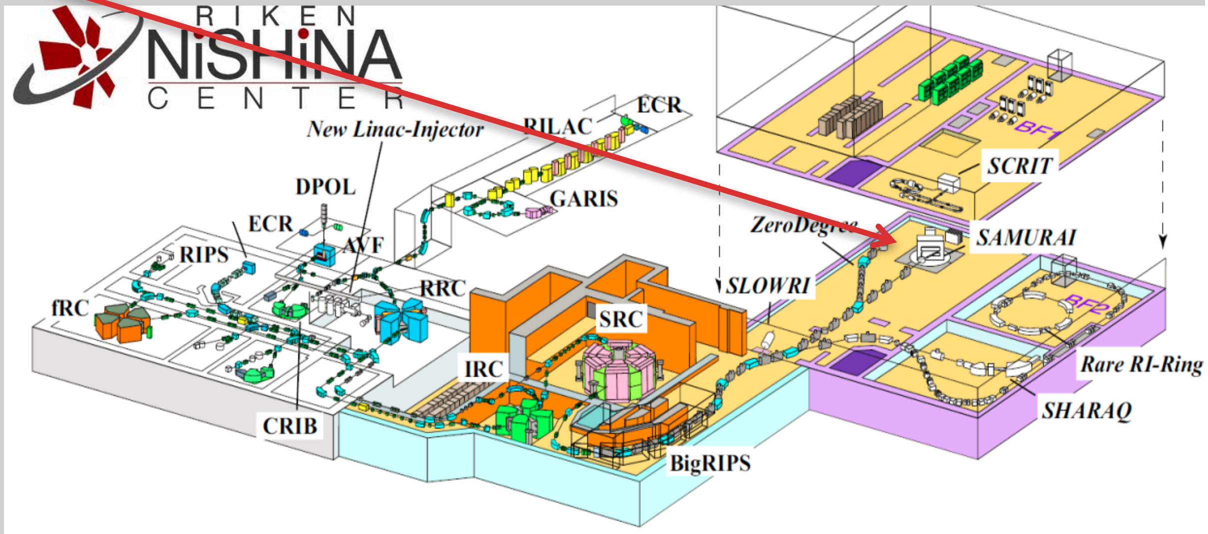
JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

The BRIKEN Project

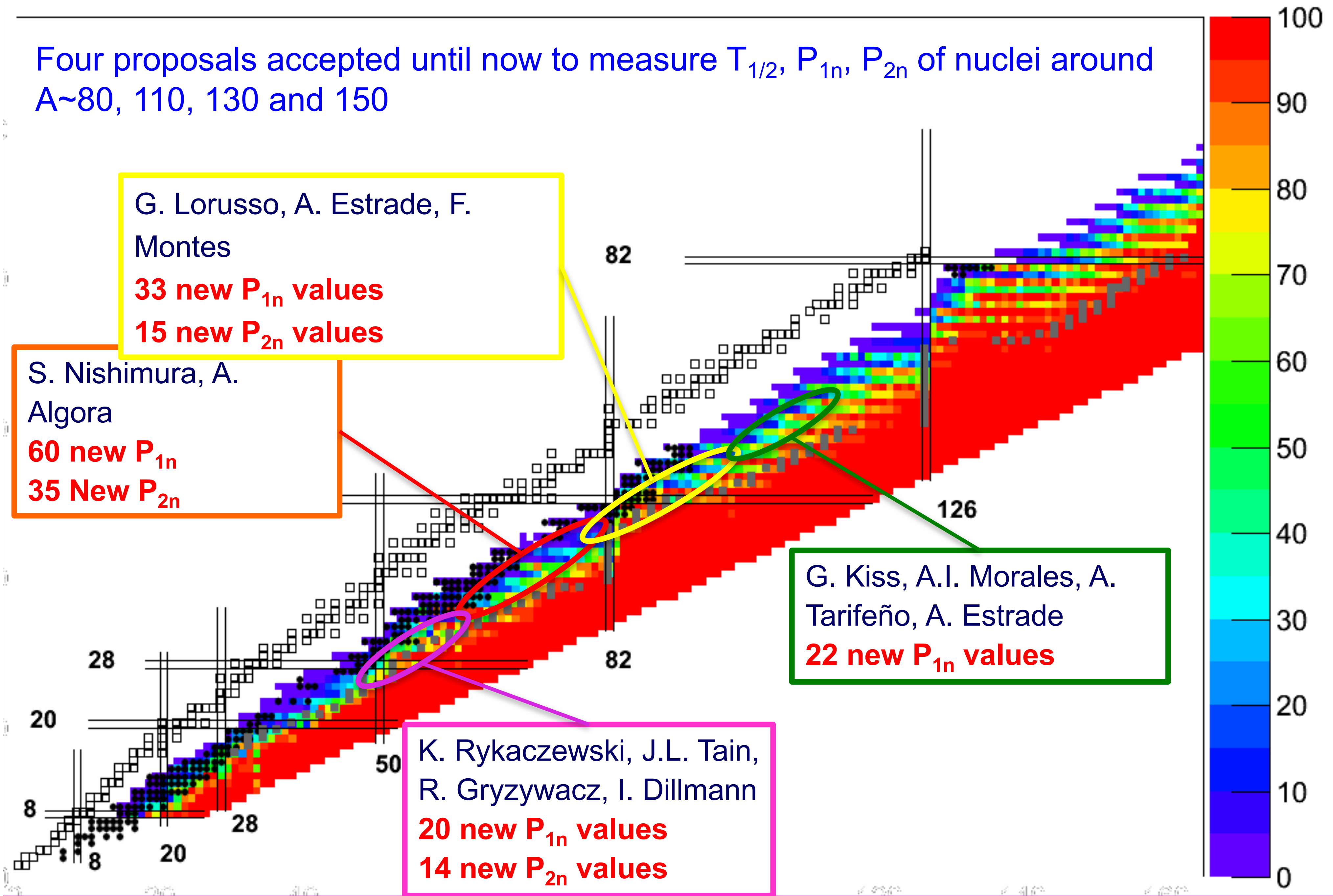
- **The largest ^{3}He moderated neutron counter**
- The AIDA implant/decay detector
- The RIBF high intensity radioactive beams
- The BigRIPS+ZeroDegree spectrometer



- **20 institutions**
- **50 participants**

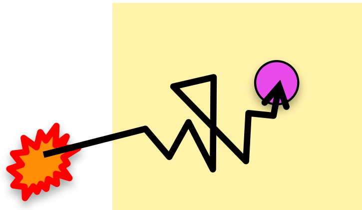


Goal: astrophysics (r-process) and nuclear structure



Moderated neutron ^{3}He counter

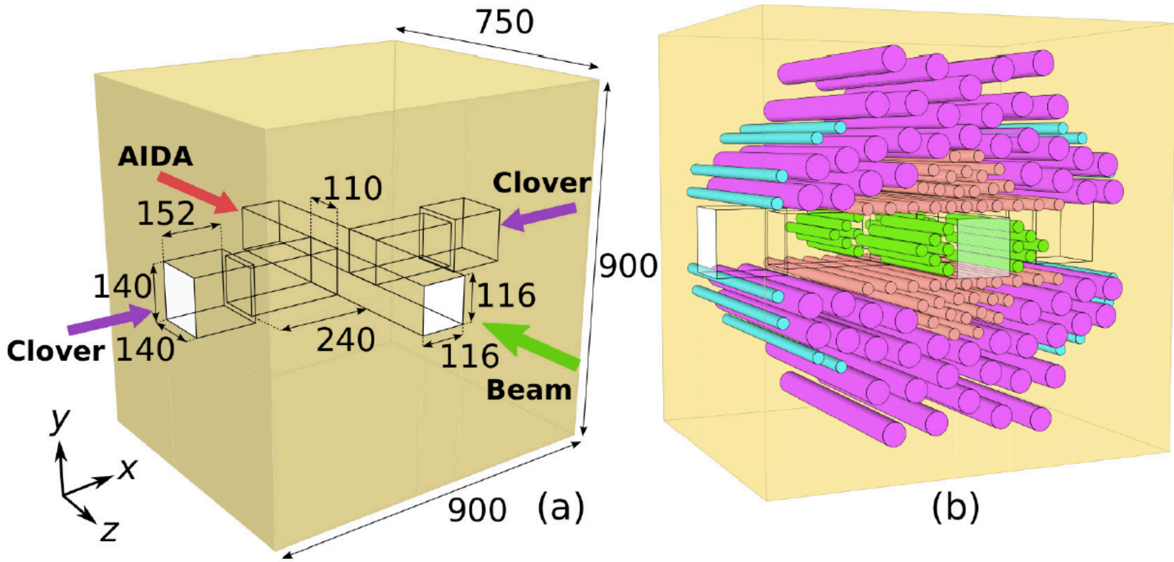
- HDPE moderator
- ^{3}He proportional tubes



$$n + {}^3He \rightarrow p + {}^3H + 764 keV$$

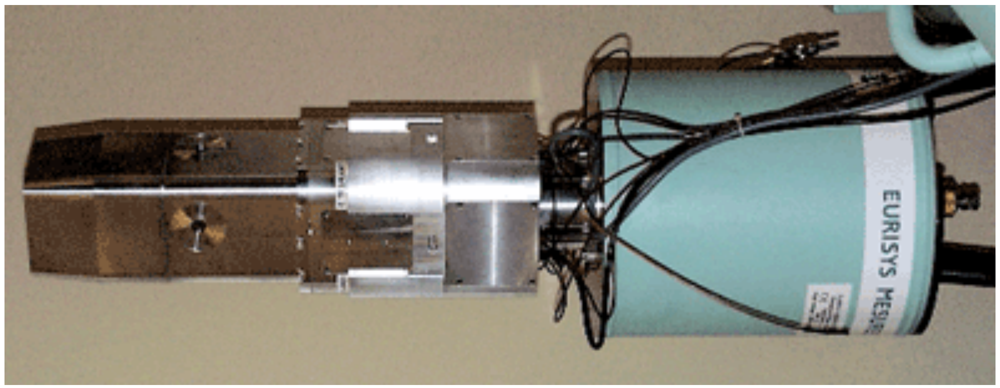
Monte Carlo optimization

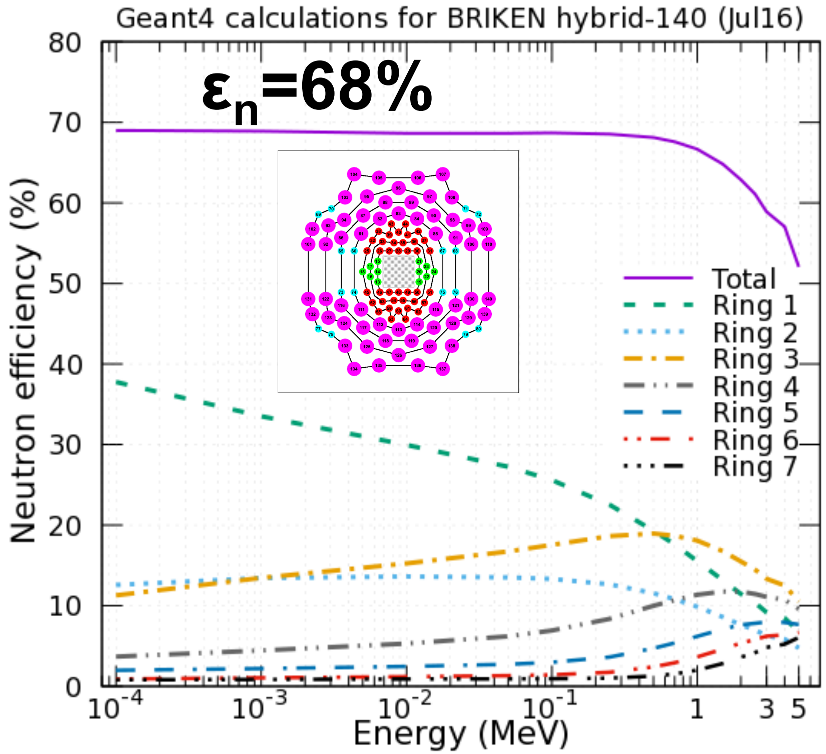
Tarifeño+, JInstr1 (2017) P04006



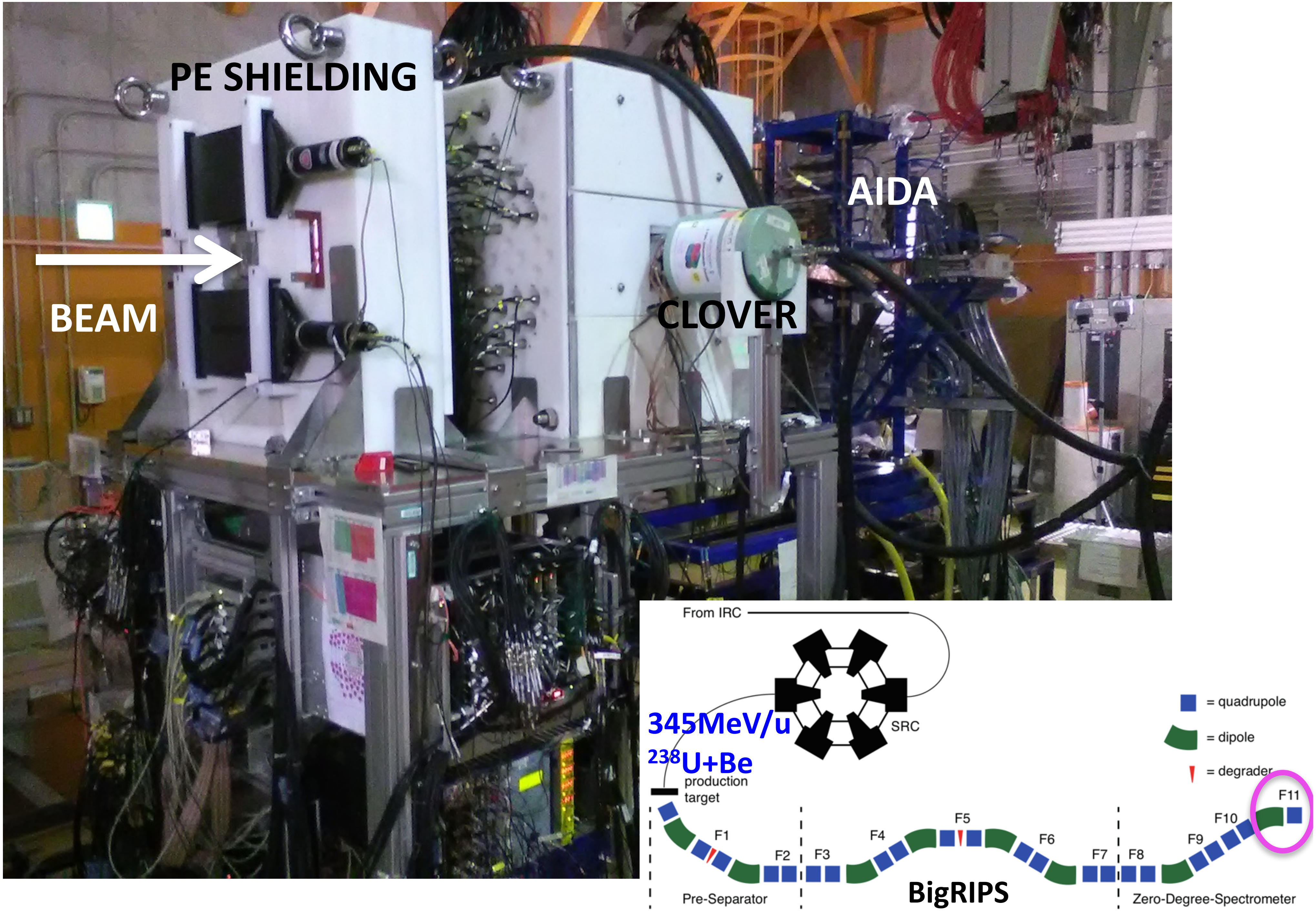
Hybrid setup:

- 140 ^{3}He tubes (4 types)
- 2 CLOVER HPGe



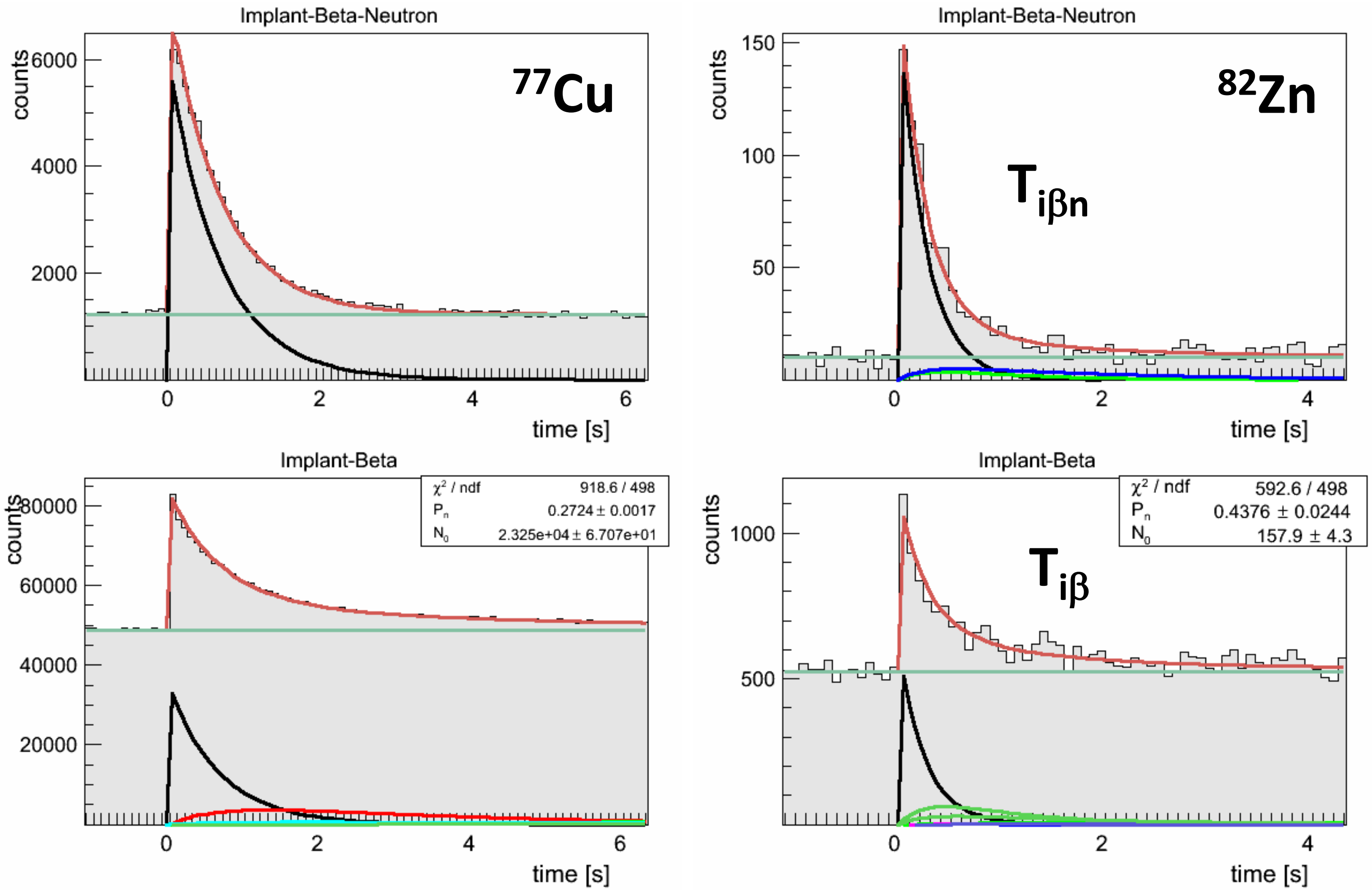


The full setup in place (F11 area)



Implant-beta-n time correlation curves

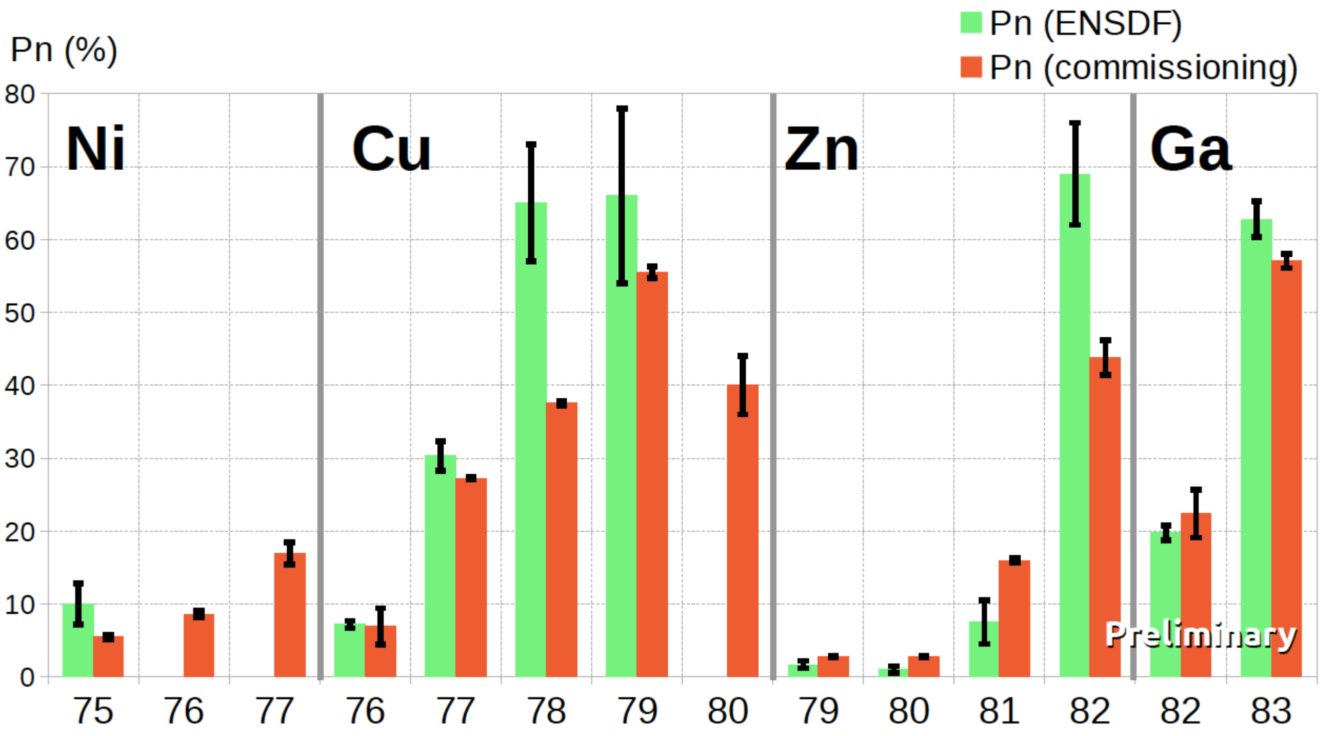
$T_{1/2}$ and P_n determination: examples



$$Fit\ function: \sum_{k\in\beta} \lambda_k N_k(t) + \sum_{k\in\beta n} \varepsilon_n P_n^k \lambda_k N_k(t) + bckg$$

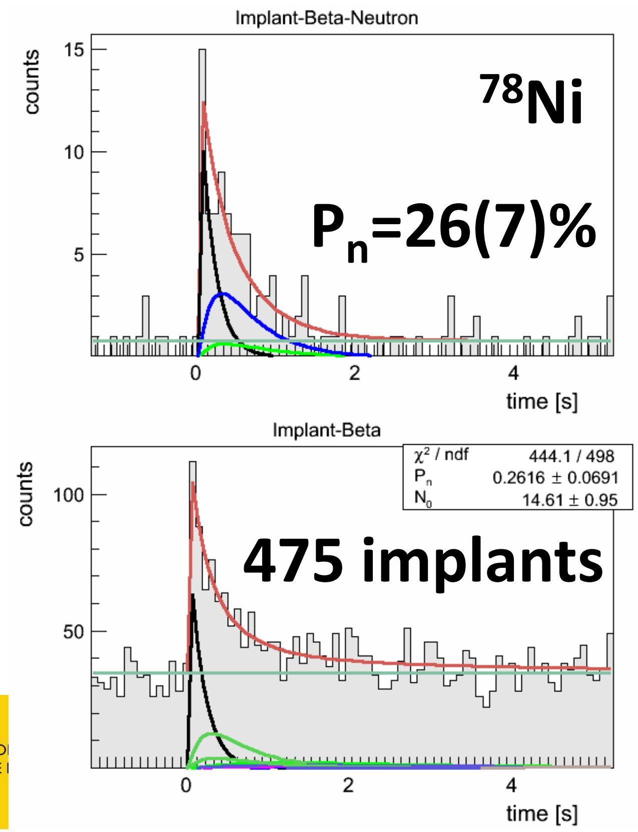
$$N_k(t) = \prod_{i=1}^{k-1} (b_{i,i+1}\lambda_i) \sum_{i=1}^{k} \frac{N_1(0)\exp(-\lambda_i t)}{\prod_{\substack{j=1 \\ j\neq i}}^{k} (\lambda_j - \lambda_i)} \quad ; \quad b_{i,i+1} = P_n^i \ or\ 1 - P_n^i$$

Summary of (preliminary) results



Improved P_n values: ^{75}Ni, ^{78}Cu, ^{81,82}Zn, new P_n values: ^{76,77}Ni, ^{80}Cu, …

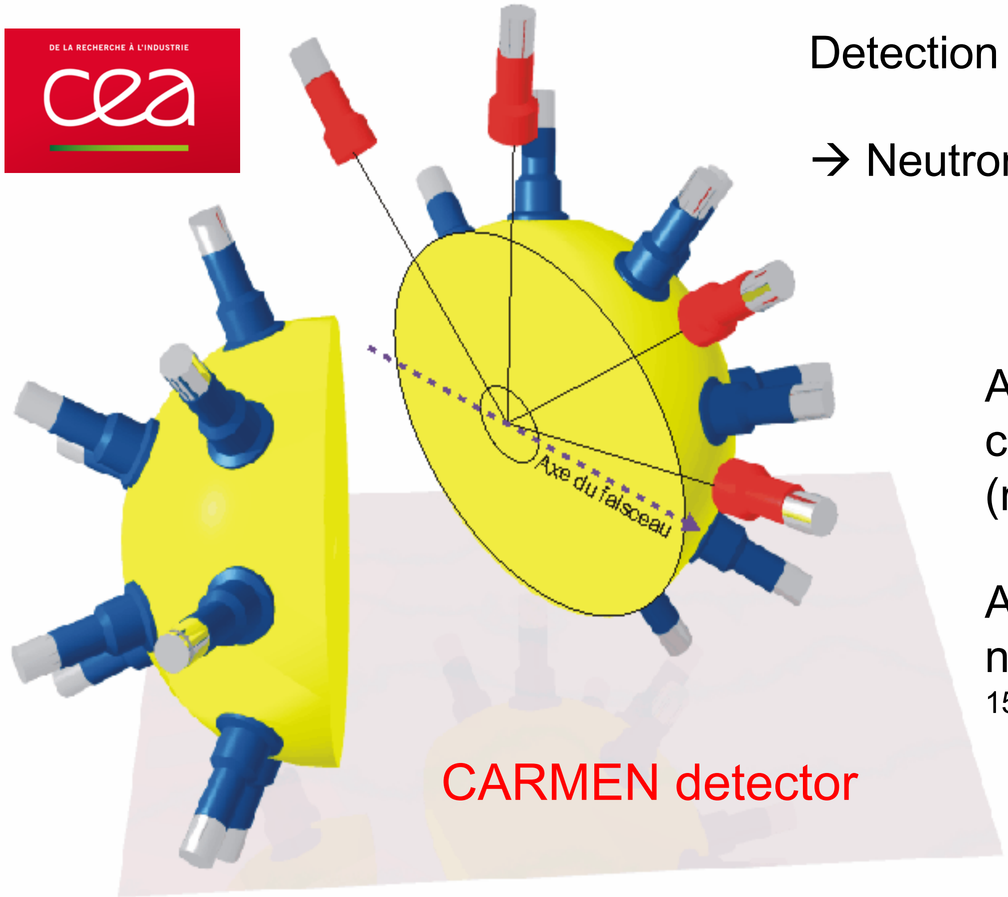
Very preliminary!



The used neutron efficiency ε_n=68% is close (^{76,77,79}Cu, ^{82}Ga) to the one determined using a ^{252}Cf source with the neutron multiplicity method ε_n=70(2)%

1st Measurement (May-June 2017)

Direct measurement of (n,xn) reaction cross sections on ^{239}Pu - G. Bélier et al.



CARMEN detector

BC521 : Gd loaded (0.5%) scintillator ~1 m^3

Detection efficiency : 85% for ^{252}Cf SF neutrons

→ Neutron counting

Active target → fission veto → improve data compared to old experiment (no fission subtraction)

Alternative techniques: correlation between the neutron scattering events and γ-rays from the $^{155,157}Gd(n,\gamma)$ reactions.

Additional needs: calibration of the detectors

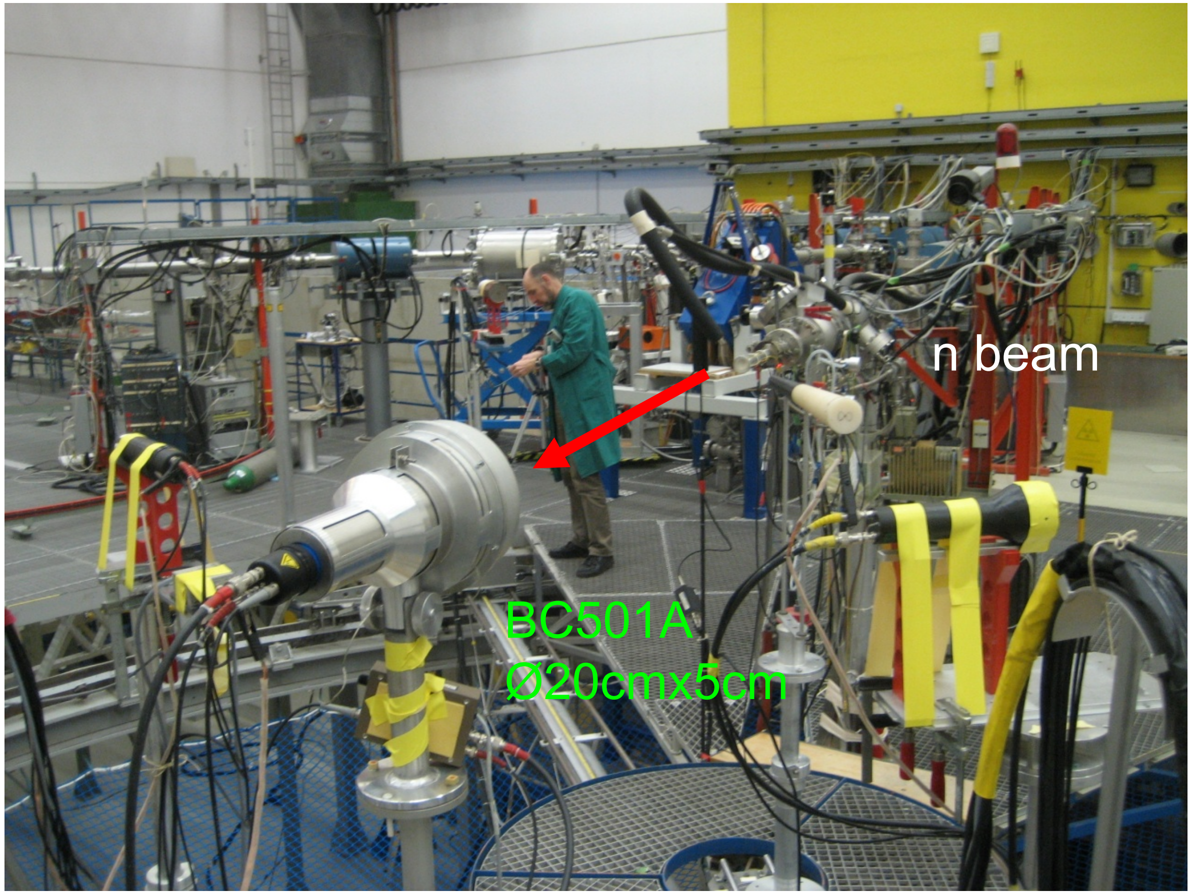
I. Metrologic-quality facilities with clean and well calibrated mono-energetic neutron beams

PTB – Germany.
NPL – UK.
Other smaller accelerators.

II. Accurate Monte Carlo simulations

Efficiency calibration of tens to hundreds of detectors.

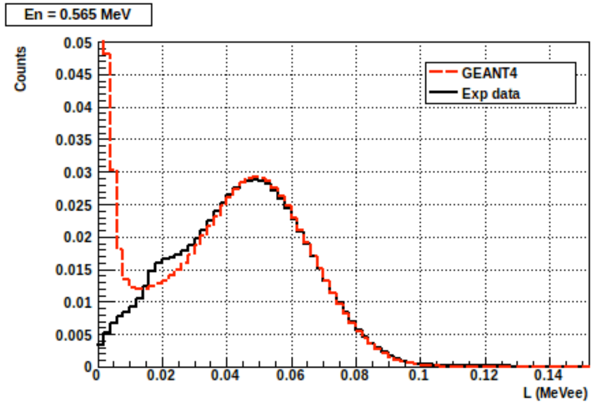
Metrologic calibration of neutron detectors

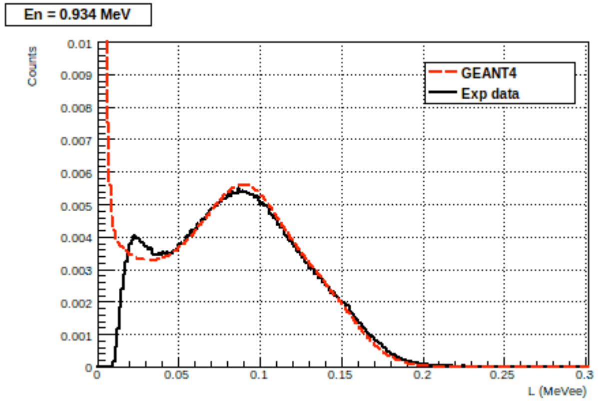


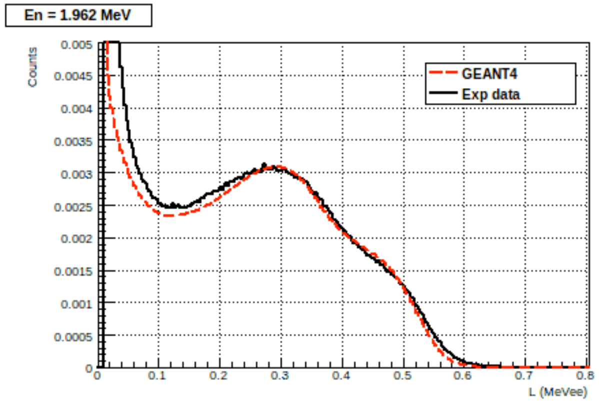
Characterisation of the detector cells at PTB-Braunschweig (Cyclotron and VdG)

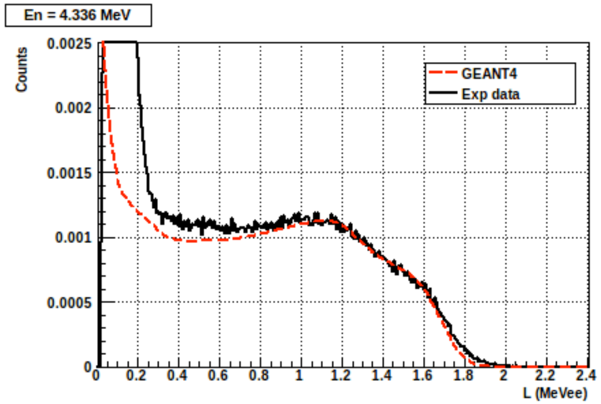
- Deuterium-Deuterium and Deuterium-Tritium reactions for E_n>5 MeV
- ^{7}Li(p,n) reaction, E_n= 0.144, 0.250, 0.565, 1.2, 2.5 MeV
- Pulsed beam (1.25MHz) for TOF background discrimination
- TOF measurement at L=1 - 2 m
- Energy calibration with sources (^{137}Cs, ^{22}Na, ^{207}Bi)

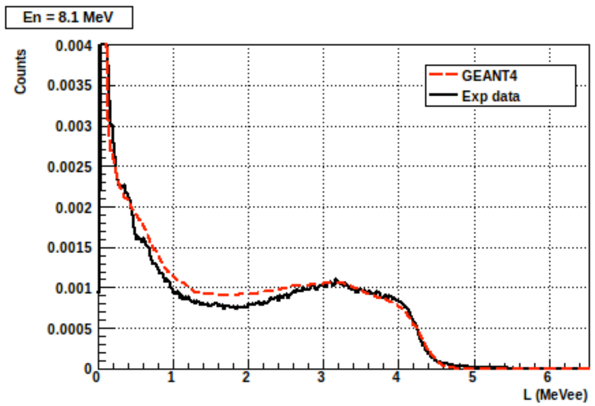
Monte Carlo simulation of the response function

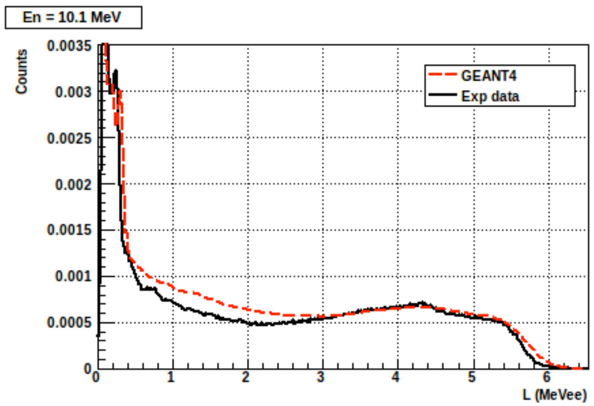












Calibrations at **PTB** and **CEA/DAM** Bruyeres Le Chatel (in collaboration with LPC-Caen):

- efficiency
- cross talk

Modified version of the GEANT4 code including the **^{12}C breakup reactions** as NRESP (PTB – metrologic quality).

Included in GEANT 4 10.04 (December 2017).

A. R. Garcia et al, NIM A 868, 73–81, (2017)

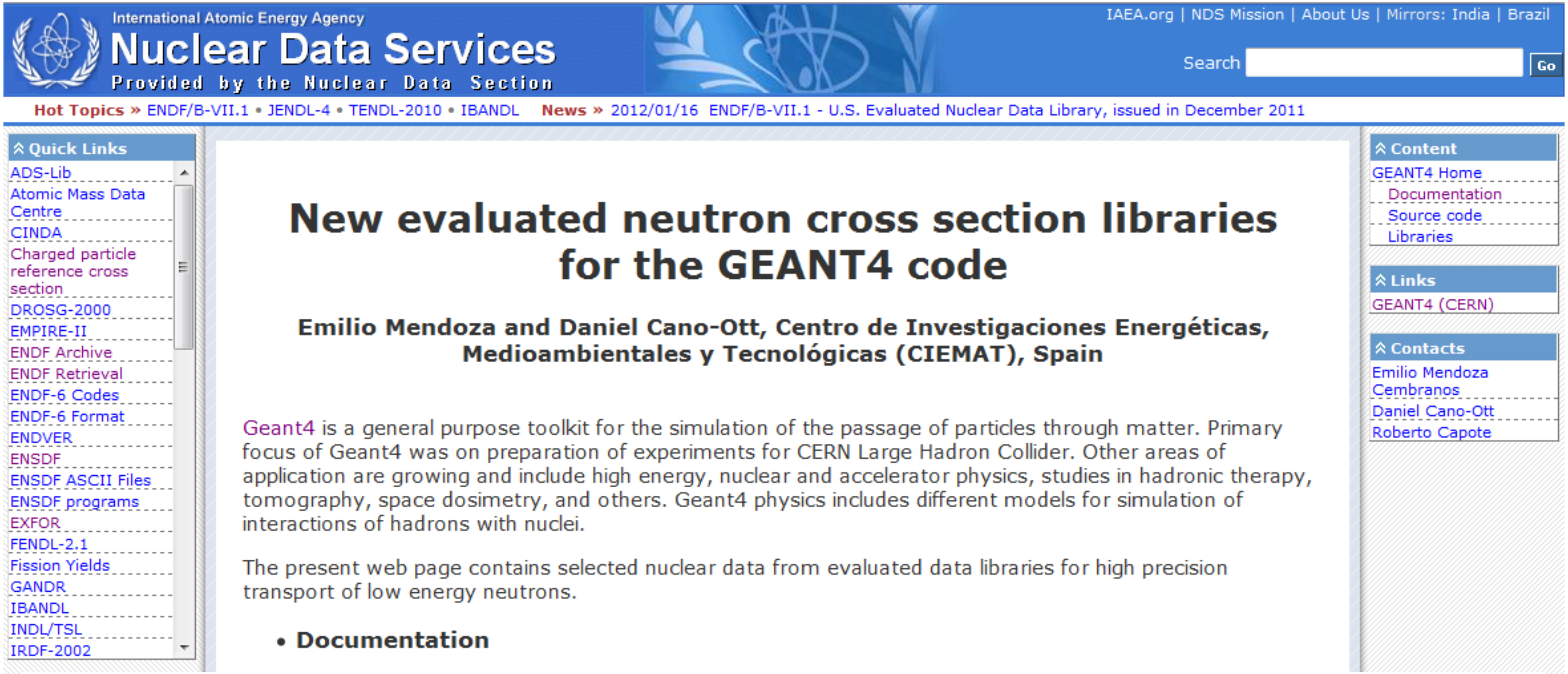
GOBIERNO DE ESPAÑA

MINISTERIO DE ECONOMÍA, INDUSTRIA Y COMPETITIVIDAD

Ciemat

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Production of nuclear data libraries for Geant 4



Theory can not predict “usable” neutron induced reaction cross sections. Need of standard evaluated neutron cross sections. CIEMAT is responsible for the production of “complete” evaluated neutron data libraries for GEANT4 at the IAEA site.

http://www-nds.iaea.org/geant4/

E.Mendoza et al. IEEE Trans. Nucl. Sci. 61, 4 (2014)

Summary and conclusions

A large variety of neutron detectors are being built or already in use in Europe and are available for experiments at EURISOL

Spectrometers (low efficiency, neutron spectroscopy)

- Well suited for β-decay (thin). MONSTER & VANDLE [&EDEN]
- Reaction studies and ancillary (thick): NEDA [& NeuLAND (inv. kin), DEMON]

4π long counters (high efficiency, no energy information)

- Well suited for β-decay: BELEN (right now as part of BRIKEN) [&TETRA]
- Fission studies: CARMEN

Operated with a new generation of **digital DAQs** for a better control of systematics (pileup, particle identification…).

Well calibrated neutron beams and accurate Monte Carlo tools are essential for producing accurate results.

What can be done at EURISOL+DF

Improve the performance / quality of experiments by combining neutron detectors (i.e. not only coordinating facilities but helping to merge different instruments):

- **Mix of fast scintillators**.
- **Mix** of **fast scintillators** and **bare ^{3}He tubes** (extending the energy range to lower energies).

Optimisation of resources and beam time.

Combination with high performance γ-ray spectrometers (and other instruments) for β-γ-n coincidence measurements (high intensities!)

- High performance Ge arrays.
- High performance $LaBr_3$ arrays (PARIS?).

ISOL vs Fragmentation for neutron detectors (keVs vs GeVs):

- ISOL facilities (are expected) to have a smaller neutron background.
- The implantation setups are less massive: μm thick computer tape + Si or plastic detectors vs massive stacks of DSSSDs.