

Progress towards a new neutron time-of-flight array for β -decay studies

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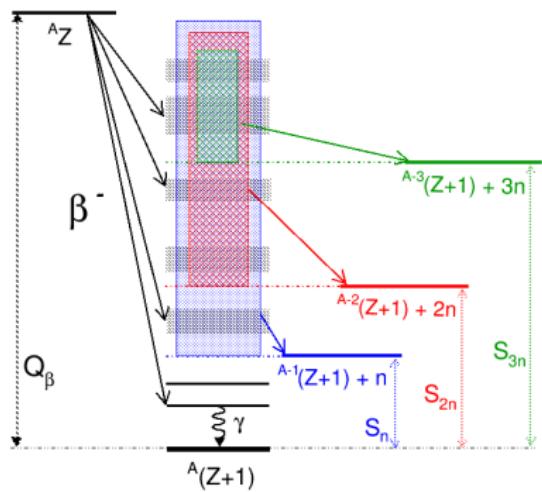
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Neutron time-of-flight array for β -decay studies

Neutron-rich nuclei: large Q_β values, loosely bound daughters

→ **β -delayed neutron emission**



- E^* , branching ratios, J^π
- $T_{1/2}$, P_n
- β -2n, β -3n emission: sequential vs direct, correlations
 - Constraints for structure models
 - Predictions of β -decay of nuclei non accessible to experiment
 - R-process calculations
 - Nuclear technology

Detection requirements for β -delayed neutron spectroscopy

- High efficiency → Low production rates, weak transitions, β -n- γ coincidences
- Delayed neutrons: $E_n \approx 0$ to 10 MeV → Low neutron energy threshold
- Good energy resolution → Level density of intermediate-mass nuclei
- Multiple-neutron detection capability → β -Xn

⇒ **Organic scintillators:**

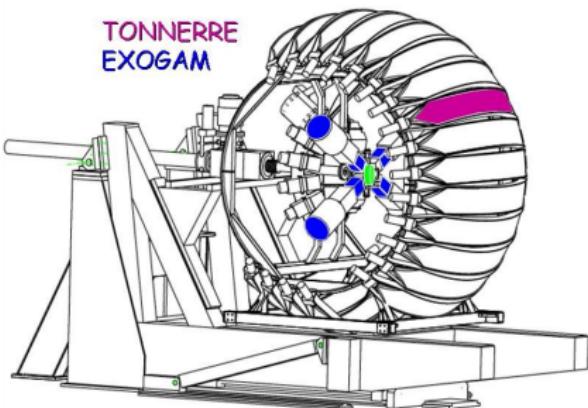
- High intrinsic efficiency
- Fast response (Time-of-flight → E_n)
- Large areas / volumes

Complementary to ^3He counter arrays (High $\epsilon_n \rightarrow P_n, P_{2n}, \dots$, but no E_n or θ_{nn})

Current β -delayed neutron arrays: TONNERRE

LPC Caen, IFIN Bucharest

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

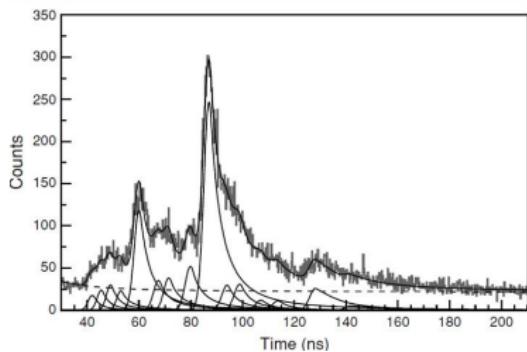


- 32 bars, $160 \times 20 \times 4 \text{ cm}^3$
- BC400 plastic scintillator
- E_n from TOF ($d_{\text{flight}} = 1.2 \text{ m}$)
- E_n resolution $\approx 10 \%$ FWHM
- Pos. resolution along bar $\approx 10 \text{ cm}$ FWHM
- Up to 45 % of 4π
- Intrinsic $\epsilon_n \approx 45 \%$ at 1 MeV

TONNERRE: Limitations

^{52}K $\beta\text{-}1n$, ISOLDE

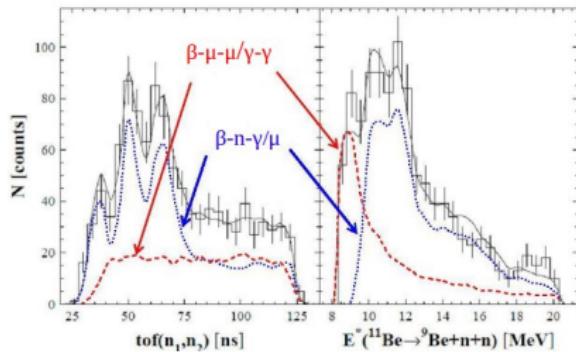
F. Perrot et al., PRC 74,014313 (2006)



- $\delta E_n / E_n$ limited by thickness & d_{flight}
- Asymmetric TOF lineshape
- Threshold: $E_n \approx 300$ keV
- No discrimination \rightarrow background

^{11}Li $\beta\text{-}2n \rightarrow E_{n1,2}$ & θ_{nn}

F. M. Marqués et al., LISE3, GANIL



No neutron- γ discrimination
 \rightarrow 80-90 % of random coincidences
(β -rays, γ -rays, cosmic muons)

Strategies for an improved neutron TOF array

From “Workshop on neutron detectors for DESPEC-FAIR and other facilities”
(CIEMAT, Madrid, July 2006)

- **Reduce background**

- ▷ Neutron- γ discrimination: liquid scintillator (and solid scintillators)

- **Improve energy resolution**

- ▷ Increase flight distance (≥ 2 m $\rightarrow \delta E_n/E_n \leq 5\%$)
(Keep thickness ≈ 5 cm for intrinsic efficiency)

- **Reduce lineshape asymmetry**

- ▷ Small volume scintillators, large PMTs

- **Lowest possible threshold for neutrons**

- ▷ Small volume scintillators, large PMTs
 - ▷ Digital electronics

- **Multiple neutron detection**

- ▷ Background reduction: n- γ discrimination
 - ▷ Cross-talk reduction: modular array, variable geometry

Detector design

Collaboration with D. Cano-Ott et al. (MONSTER array for DESPEC-FAIR)

→ Common proposal for SPIRAL2-DESIR TDR (Jan. 2009)

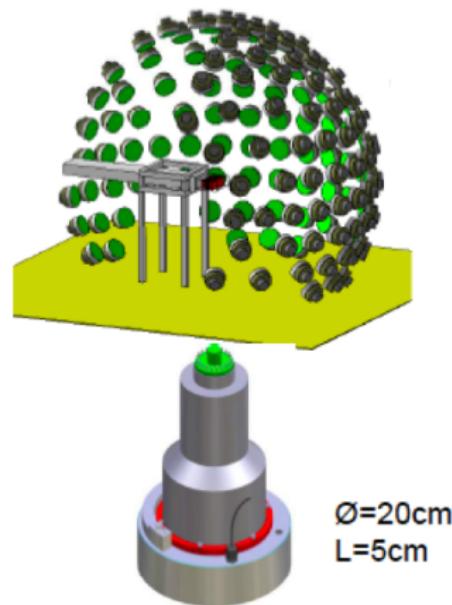
- Modular array (\approx 100 modules, 30 built)

- **Module design**

- ▷ 5 cm thick, 20 cm in diameter
 - ▷ Liquid scintillator (BC501A/EJ301)
 - ▷ Large-diameter (\approx 13 cm) PMT
 - ▷ Light-guide

- Similar to EDEN (IPNO, KVI)
Neutrons from GR excited by reactions
(H. Laurent *et al.*, NIM A326 (1993) 517)
(3 EDEN modules at LPC for tests)

- Digital electronics



Digital electronics & DAQ: FASTER project¹

- Single-channel FPGA-based digital functions
→ **Spectroscopy amplifier + ADC, CFD + QDC**

4-channel NIM-size module



48-channel crate (MicroTCA standard)



- **Spec. amp. + ADC:** 125 Ms/s, 14 bits, range ≤ 10 V, BW 25 MHz
- **CFD + QDC:** 500 Ms/s, 12 bits, range 2.3 V, BW 100 MHz
- Time-stamping, no common dead time, baseline correction, sample writing mode, oscilloscope...

¹D. Etasse et al., LPC Caen, faster.in2p3.fr

Digital n- γ discrimination

The Principle of n- γ Pulse Shape Discrimination

Charged particles with different specific energy losses $\frac{dE}{dx}$

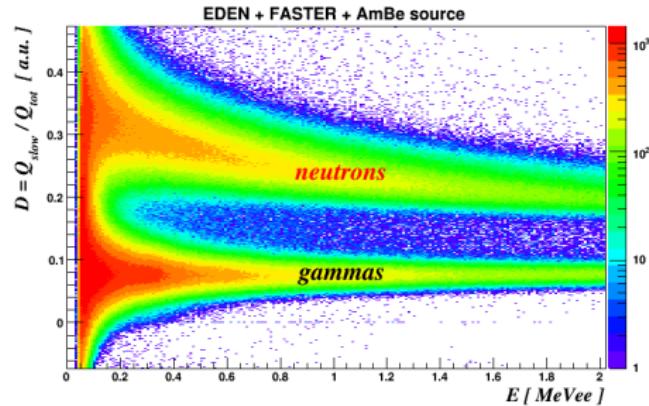
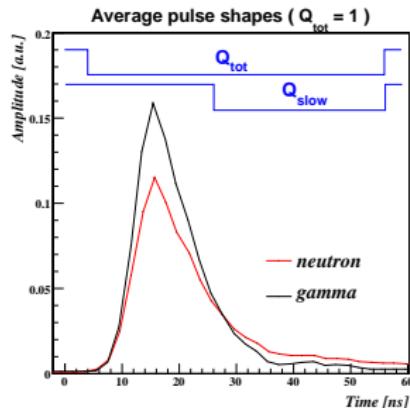
→ Different scintillation pulse shapes

→ “Pulse Shape Discrimination” (PSD)

E.g. protons & electrons (→ neutrons & γ -rays), α -rays & electrons

PSD → discriminating variable D sensitive to pulse shape

E.g. “charge comparison”: $D = Q_{slow}$ or Q_{slow}/Q_{tot}

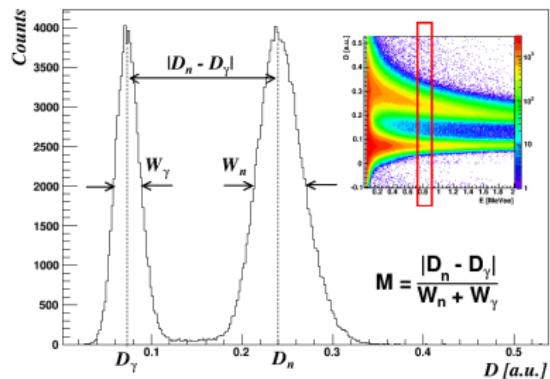


Digital n- γ discrimination

Discrimination quality

Figure of Merit M

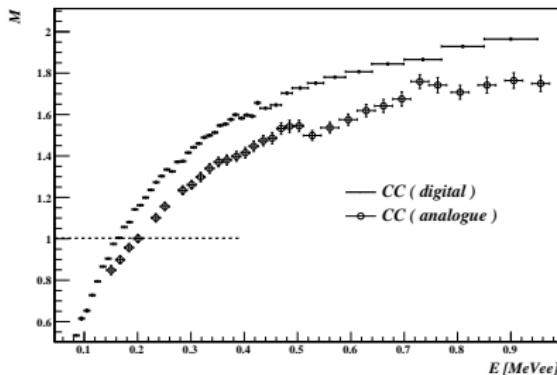
Example with $M = 1.83$



FASTER vs analogue (VME)

Charge comparison

VME: CFD+GG+Delays+QDCs



Digital DAQ: other methods tested with n sources and monoenergetic n's
→ Improvements compared to classical charge comparison

Characterisation of modules with monoenergetic neutrons

CEA Bruyères-le-Châtel, 4 MV Van de Graaf facility
Oct. 2011 & Oct. 2012

▷ EDEN & MONSTER module characterisation

- Intrinsic efficiency → Validate simulations
- Cross-talk (no data < 14 MeV) → Validate simulations & cross-talk filters²

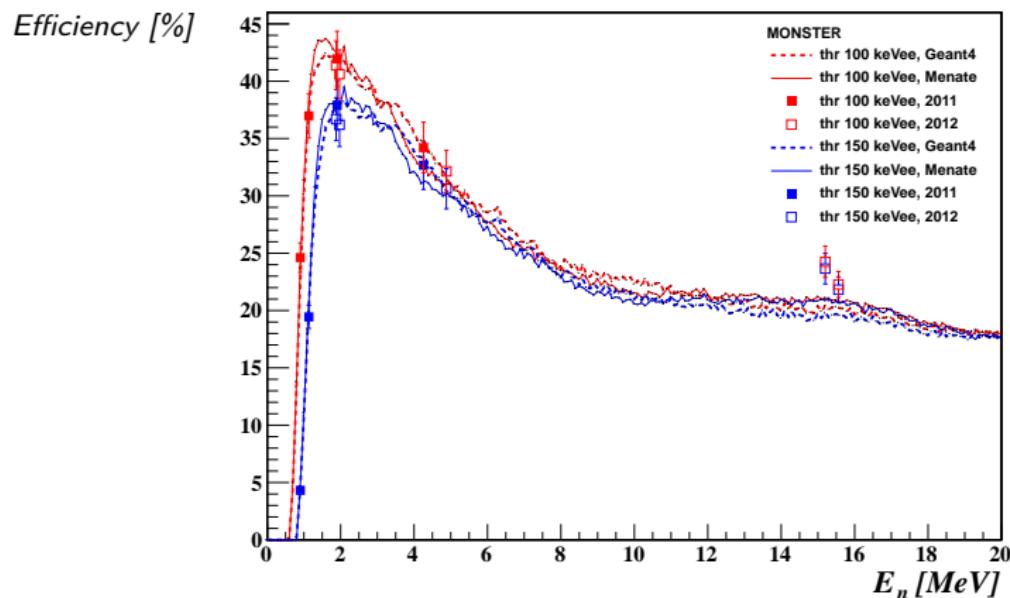
Neutron energies:

- 2011: **0.5 to 5 MeV**
- 2012: **2.1, 5 & 16 MeV**
- Reactions: p+T ($E_n < 5$ MeV), d+D ($E_n \approx 5$ MeV), d+T ($E_n \approx 16$ MeV)

→ M. Sénoville's PhD thesis

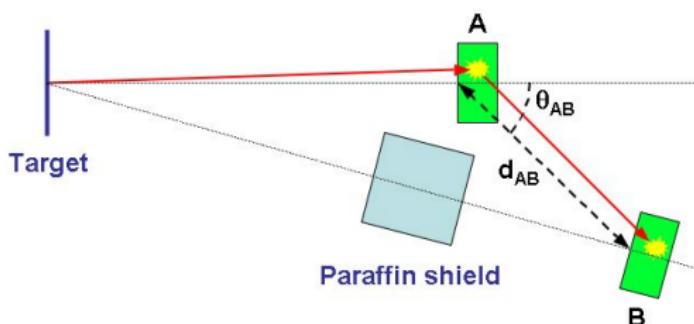
²F. M. Marqués et al., NIM A450 (2000) 109

Intrinsic efficiency - MONSTER module



MENATE: P. Désesquelles, NIM A 307 (1991) 366

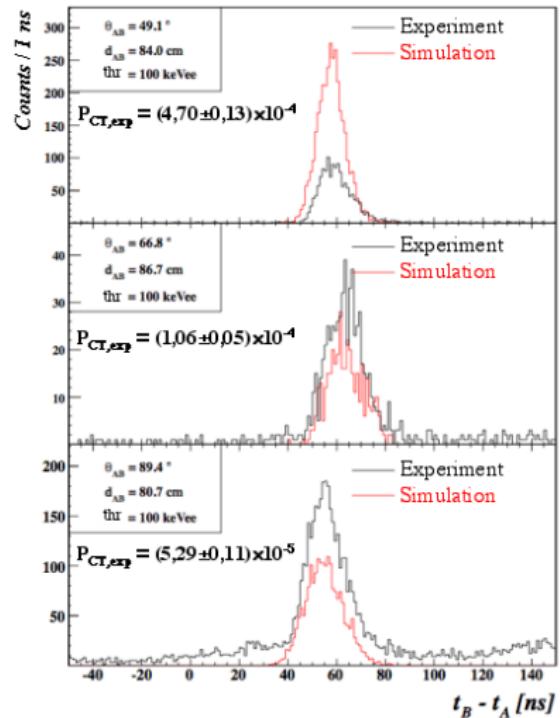
Cross-talk measurements



$E_n = 2.0 \text{ MeV}$

Threshold = 100 keVee

Cross-talk probability: $P_{CT} = (N_{AB}/N_A)$



Experiment and simulations agree within a factor 2 at all E_n and θ_{AB}
Realistic Geant4 simulations including detector structure and support structure

Alternative scintillators for lowest energies ($E_n \lesssim 1$ MeV)?

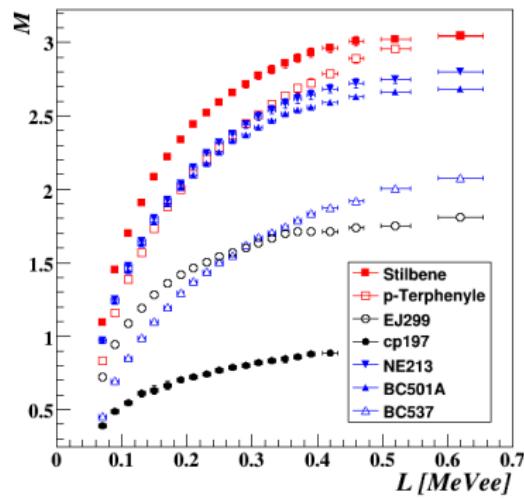
Neutron- γ discrimination quality limited

- Smaller scintillator volumes → higher light collection efficiency
- Scintillators with higher light yield and/or better discrimination
 - **Liquids:** BC501A/NE213 (for reference), BC537 (deuterated)
 - **Crystals:** p-terphenyl, trans-stilbene (Cryos-Beta, Ukraine)
 - **Discriminating plastics:** EJ299, sample from CEA/LCAE (M. Hamel)

Cylinders, 5 cm height \times 5 cm diameter

Light yields wrt BC501A/NE213:

- ① P-terphenyl: 2.2
- ② Stilbene: 1.9
- ③ EJ299: 1.3
- ④ BC537: 0.8
- ⑤ CEA: 0.6



M. Sénoville

Study of multi-neutron emission in the β -decay of ^{11}Li

ISOLDE, CERN, 3-12 October 2014

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Aarhus University: K. Riisager, M. V. Lund

ISOLDE CERN: M.J.G. Borge, M. Madurga

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VECC Kolkata: C. Bhattacharya, K. Banerjee

IFIC Valencia: A. Algora

CEA/SPhN Saclay: M. Sénoville

Universidade de Santiago de Compostela: B. Fernandez

IPN Orsay: M. Assié

Study of multi-neutron emission in the β -decay of ^{11}Li

Motivation

^{11}Li β -decay

$Q_\beta = 20.6$ MeV and weakly bound daughter
→ Variety of delayed particle emissions:
 $1n$ (85 %), $2n$ (4 %), $3n$, $n+\alpha$, d , t ...

No β - $2n$ spectroscopy

Delayed $1n$ emission still unclear

Goals

Detect 2 delayed neutrons in coincidence

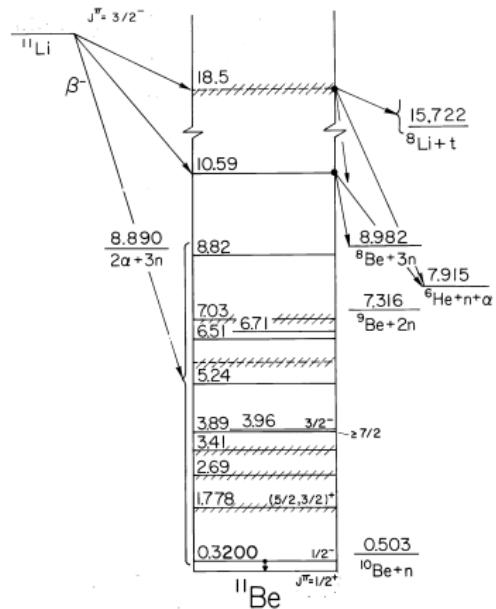
Neutron array → θ_{nn} , $E_{n1,2}$, $n-\gamma$ discrimination

→ Correlation studies between delayed neutrons?

→ Sequential or simultaneous emission?

→ Correlated or uncorrelated neutrons?

+ Improved picture of delayed $1n$ emission



Experimental setup

^{11}Li beam

Protons (1.4 GeV, 2 μA) + Ta target
Re surface ionisation source + RILIS
50-keV, 1300 ions/s
6 days

39 neutron modules

29 MONSTER, 4 EDEN, 6 CEA

Near array: $d = 1.5 \text{ m}$

$\Omega = 3\%$ of 4π

$\delta E = 60 \text{ keV}$ at 1 MeV

→ n-n coincidences

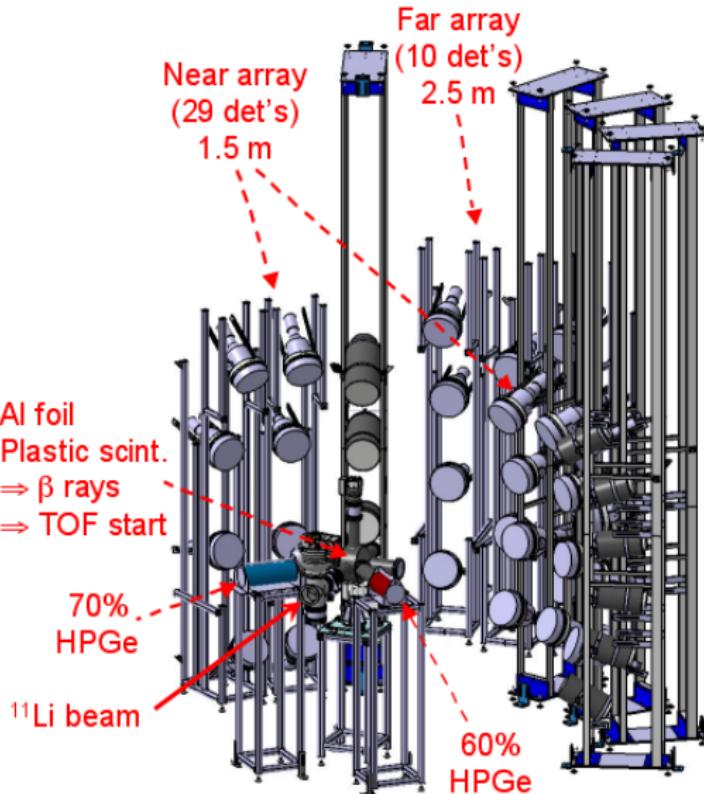
Far array: $d = 2.5 \text{ m}$

$\Omega = 0.3\%$ of 4π

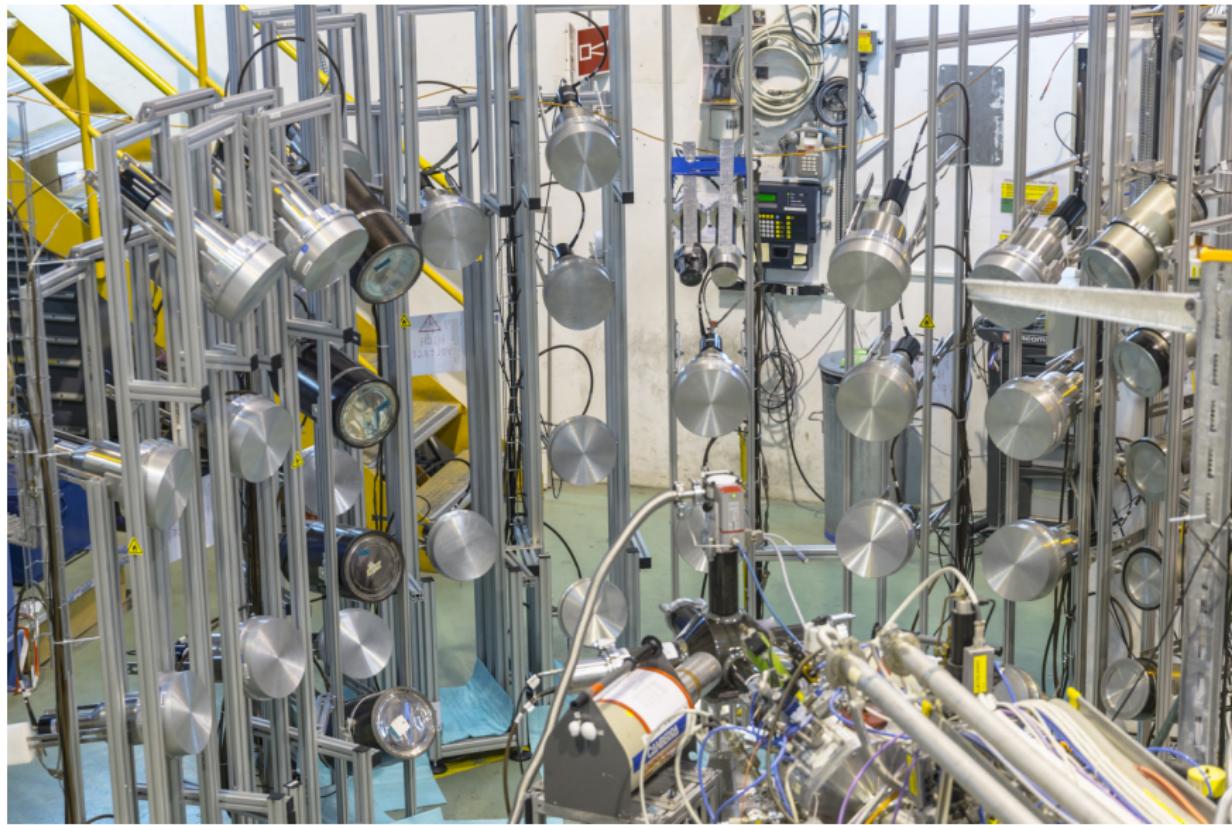
$\delta E = 35 \text{ keV}$ at 1 MeV

→ Improved $\beta^+ \text{n}$ data

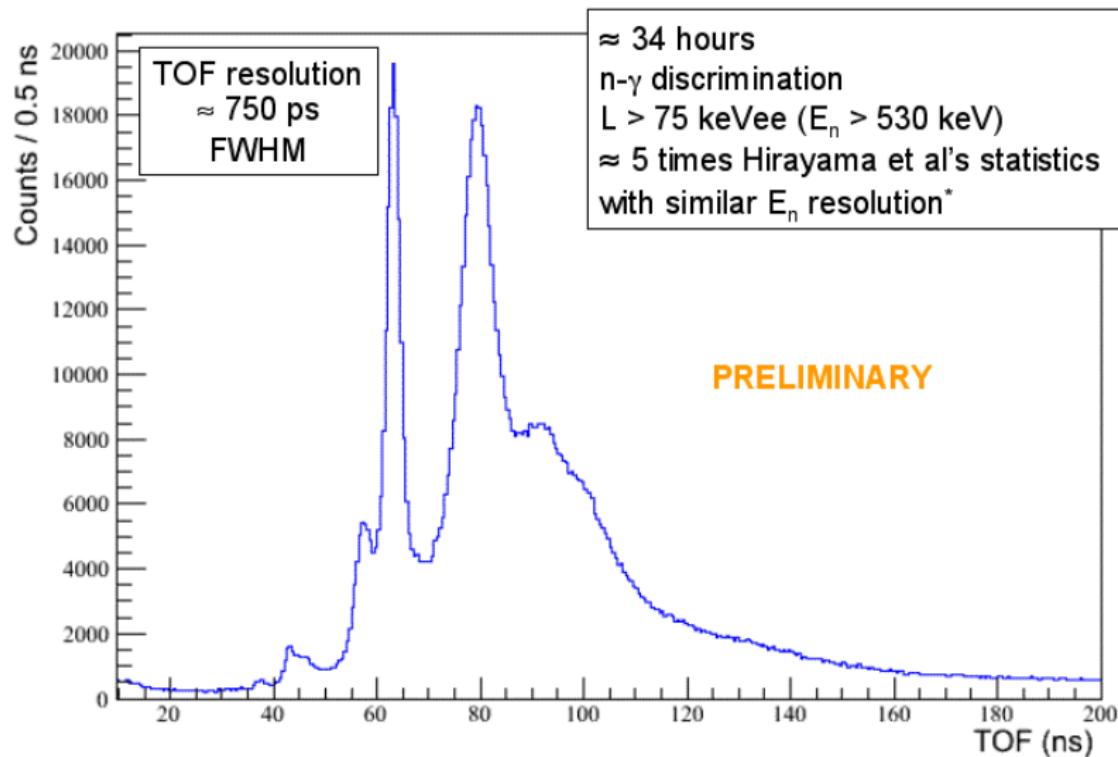
Digital electronics (FASTER, LPC)



Experimental setup

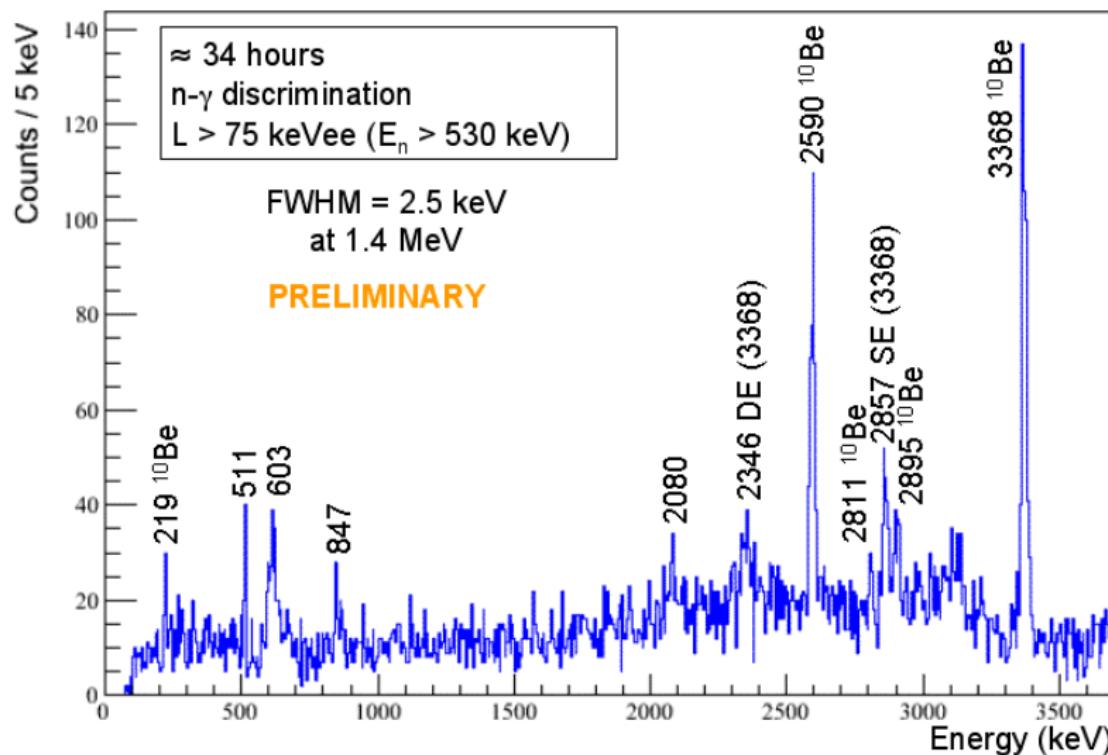
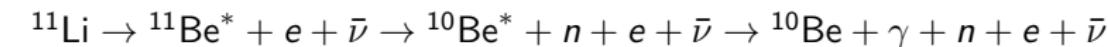


^{11}Li β -1n - Near Array



* Hirayama et al., PLB 611 (2005) 239

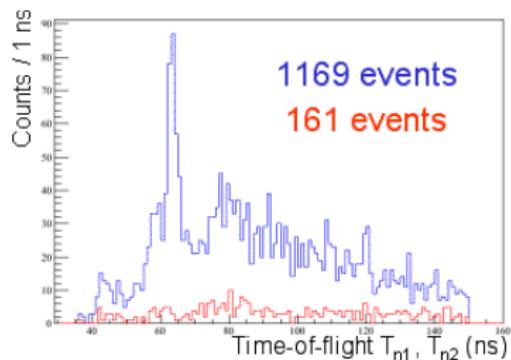
^{11}Li β -n- γ - Near Array and 60 % Ge detector



^{11}Li β -2n

37 h (25 %), near array, $T_\beta - T_{impact} < 120$ ms, n- γ discrimination, $L > 0.1$ MeVee

PRELIMINARY

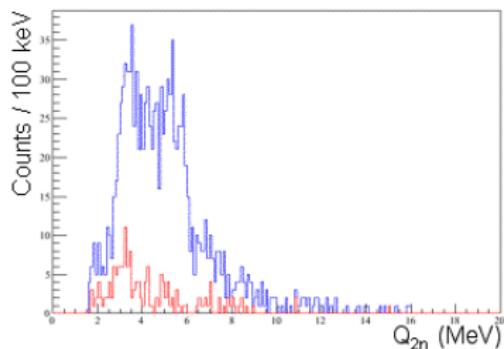
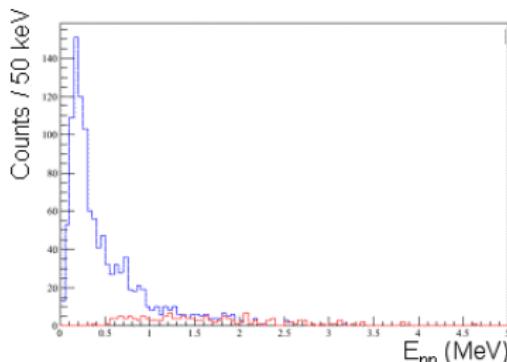


1st order crosstalk rejection: $d_{12} > 1.4$ m

Full beam time $\rightarrow \approx 600$ events
 ≈ 1000 events expected

$$Q_{2n} = E_1 + E_2 + \frac{m_n}{m_{^9\text{Be}}} (E_1 + E_2 + 2\sqrt{E_1 E_2} \cos \theta_{nn})$$

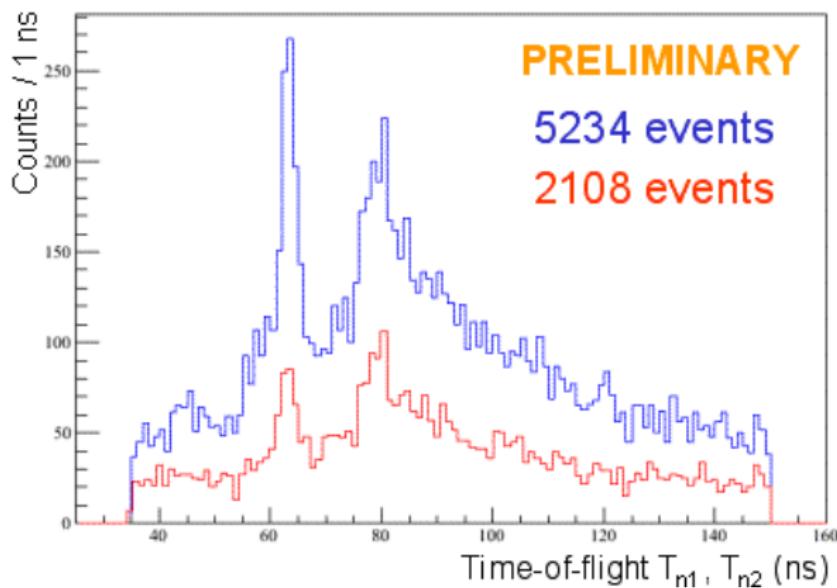
$$E_{^9\text{Be}}^* = Q_{2n} + S_{2n}$$



^{11}Li β -2n - Without n- γ discrimination

37 h (25 %), near array, $T_\beta - T_{impact} < 120$ ms, $L > 0.1$ MeVee

$$d_{12} > 1.4 \text{ m}$$



Conclusions

- Development of a TOF array for β -delayed neutron spectroscopy
- Goal: Improved characteristics compared to previous arrays
- Emphasis on digital DAQ, low threshold, energy resolution, background reduction ($n-\gamma$ discrimination), multiple neutrons (cross-talk)
- Module design characterised with sources and monoenergetic neutrons (Efficiency & cross-talk)
- Neutron- γ discrimination of crystal, liquid and plastic scintillators compared
 - Small crystals or BC501A/EJ301 cells interesting for low energies
 - Plastic scintillators not competitive
- Proof of principle of β -2n studies with a TOF array: $^{11}\text{Li}-\beta$ -2n, ISOLDE (Analysis in progress...)