Nuclear structure far from stability with low-energy beams

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CNRS-TRIUMF IRL Workshop, TRIUMF, April 23, 2026

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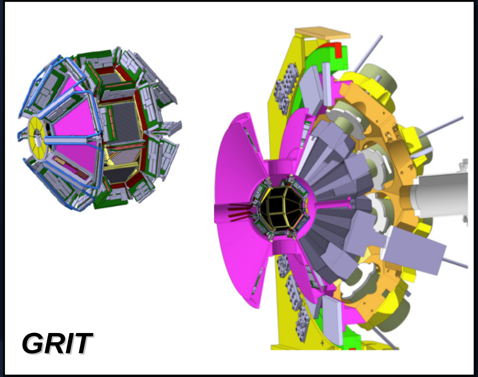
Nuclear structure at low energy (< 20 AMeV)

- **Transfer reactions : (d,p), (d,t)...**
  - **GANIL** : TIARA / MUGAST + EXOGAM / AGATA (+VAMOS)
  - **TRIUMF/ISAC-II** : SHARC + TIGRESS, ACTAR
  - **R&D GRIT** → GANIL/SPIRAL1, LNL/SPES
  - **Collaborations** : USC, Surrey, IJCLab, LNL...

  → **Shell structure** in moderately neutron-rich nuclei

  → **Constrain models** → Improve predictions close to dripline



- **R&D for β-delayed neutron spectroscopy**

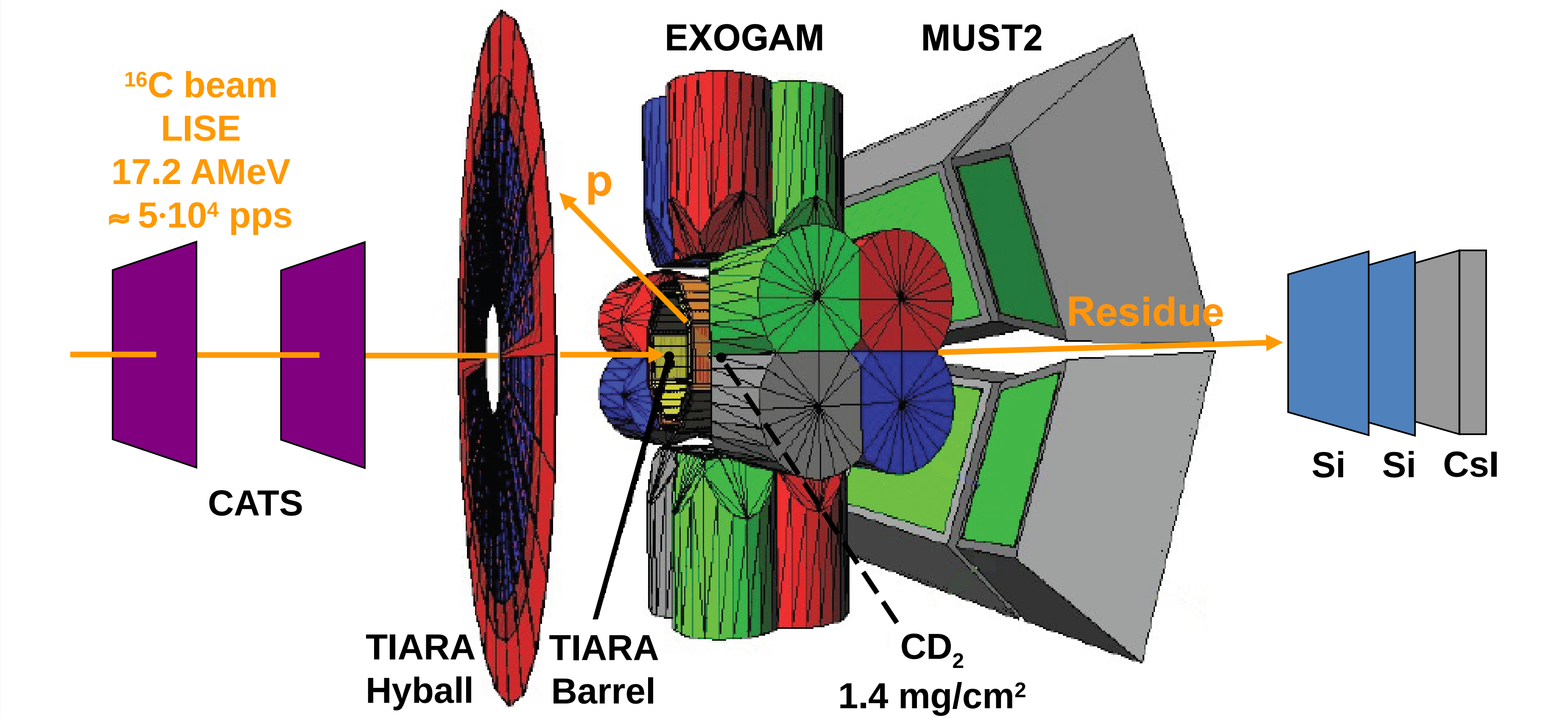
  → Multiple neutron emission → multi-neutron correlations

- Complementary to studies at high energy (~250 AMeV) at RIKEN/RIBF

  (Nucleon knockout, breakup → inv. mass spectroscopy, multi-neutron correlations...)

$^{16}C(d,p)^{17}C$ at GANIL

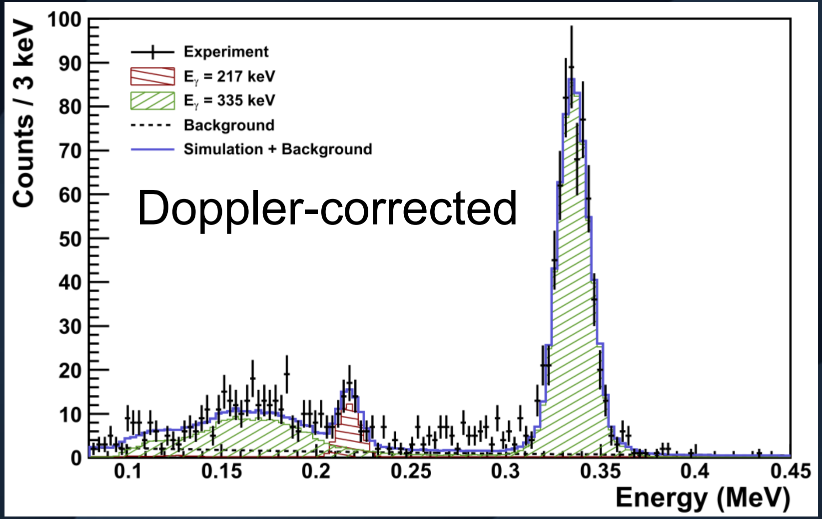
- Locate the $\nu 1s_{1/2}$, $\nu 0d_{5/2}$ and $\nu 0d_{3/2}$ sp strength
  → N = 14 and 16 shell gaps

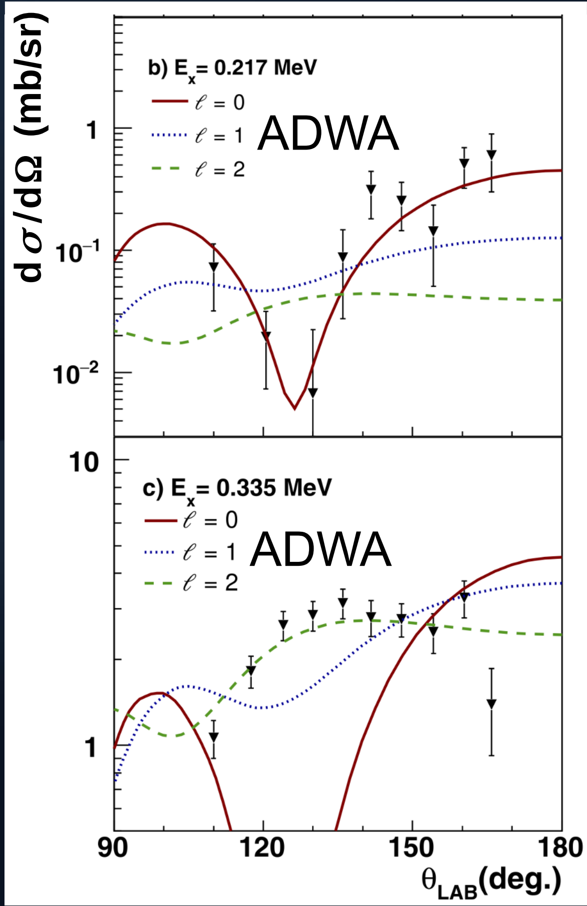


$^{16}C(d,p)$ – ^{17}C bound states

X. Pereira-López, PhD USC/UNICAEN
PLB 811, 135939

Coincidences : proton (TIARA) + γ-ray + Z=6 residue





ADWA calculations

→ Angular momentum transfer ℓ

→ Spectroscopic factors C^2S

^{16}C(d,p) – ^{17}C bound states

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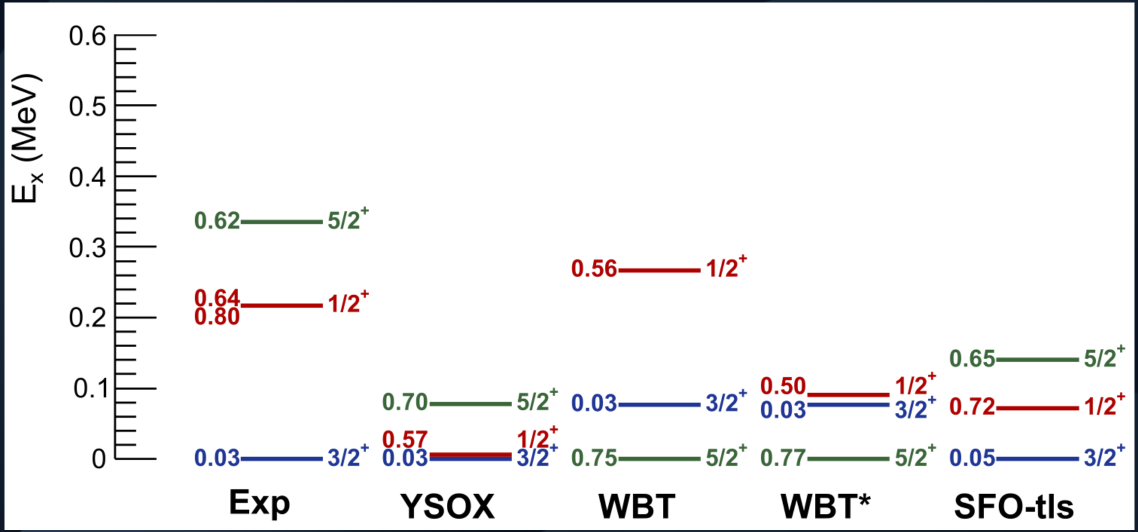


- **$1/2^+$ and $5/2^+$ states**
  - Large C^2S
  - Nearly degenerate

→ No sub-shell closure at N=14

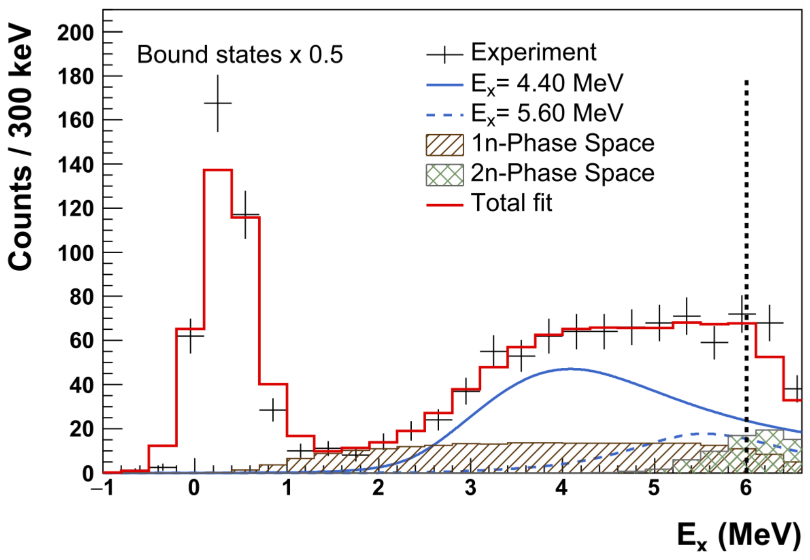
- **$3/2^+$ gs**
  - Very small C^2S

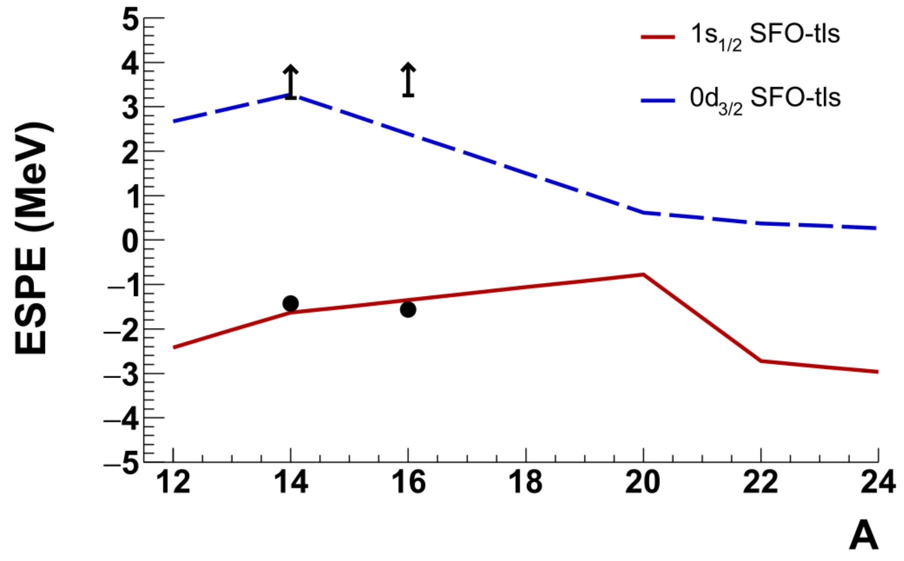
→ $\nu 0d_{3/2}$ strength unbound

- Good agreement with shell model

$^{16}C(d,p)$ – ^{17}C unbound states

J. Lois-Fuentes, PhD USC
PLB 867, 139600





- E_x → Widths
- γ-rays → BR for n decay to $^{16}C(2^+)$
- Cross-section / ADWA calculations

→ $3/2^+$ resonance(s)

→ N=16 gap > 5.08 MeV

→ 1.3 MeV larger than in shell-model

→ Predictions for N=16 ^{22}C?

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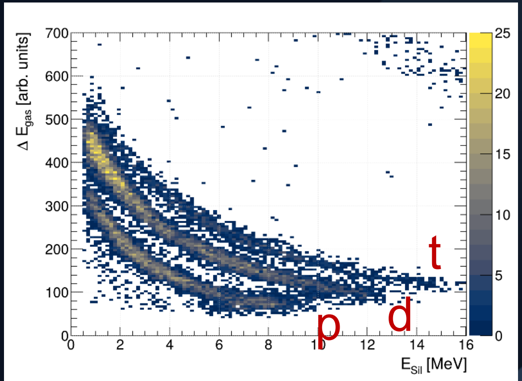
$^{16}C(d,p)^{17}C$

X. Pereira-López [1,2], J. Lois-Fuentes [1], B. Fernández-Domínguez [1], F. Delaunay [2], N.L. Achouri [2], N. A. Orr [2], W. Catford [3], M. Assié [4], S. Bailey [5], B. Bastin [6], Y. Blumenfeld [4], R. Borcea [7], M. Caamaño [1], L. Caceres [6], E. Clément [6], A. Corsi [8], N. Curtis [5], Q. Deshayes [2], F. Farget [6], M. Fisichella [9], G. de France [6], S. Franchoo [4], M. Freer [5], J. Gibelin [2], A. Gillibert [8], G. Grynier [6], F. Hammache [4], O. Kamalou [6], A. Knapton [3], T. Kokalova [5], V. Lapoux [8], B. Le Crom [4], S. Leblond [2], F.M. Marqués [2], A. Matta [3], P. Morfouace [4], J. Pancin [6], L. Perrot [6], J. Piot [6], E. Pollacco [8], D. Ramos [1], C. Rodríguez-Tajes [1,6], T. Roger [6], F. Rotaru [7], M. Sénoville [8], N. de Séréville [4], R. Smith [5], O. Sorlin [6], M. Stanoiu [7], I. Stefan [4], C. Stodel [6], D. Suzuki [4], J.C. Thomas [6], M. Vandebrouck [6], J. Walshe [5], C. Wheldon [5],
J.A. Lay [10], N. Michel [11], A. Moro [10], T. Otsuka [12], M. Płoszajczak [6], P. Punta [10], T. Suzuki [13], N. Timofeyuk [3]

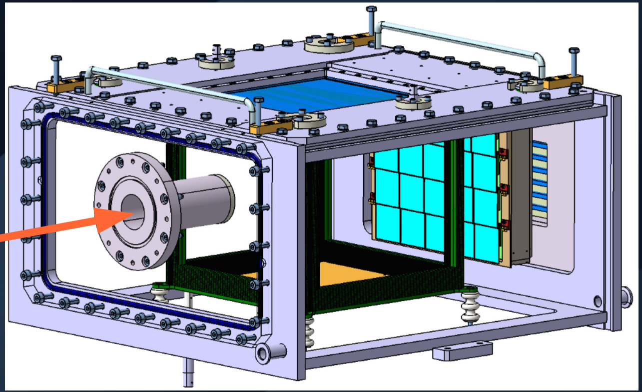
[1] Univ. Santiago de Compostela, [2] LPC Caen, [3] Univ. Surrey, [4] IJCLab Orsay, [5] Univ. Birmingham, [6] GANIL, [7] IFIN-HH Bucharest, [8] CEA/IRFU/SPhN Saclay, [9] LNS Catania, [10] Univ. Sevilla, [11] IMP Lanzhou, [12] Univ. Tokyo, [13] Nihon Univ.

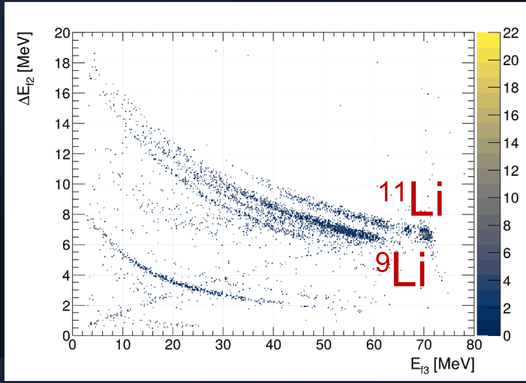
^{11}Li(d,p) with ACTAR-TPC at TRIUMF

- Structure of unbound ^{12}Li



PID: Light particles
(Si detectors)

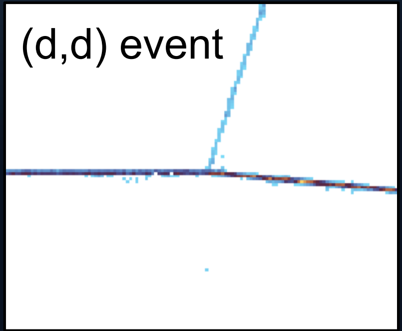




PID: Heavy particles
(Si detectors)

^{11}Li beam at 7.5 AMeV
~2000 pps × 5 days
D_2+CF_4 (95+5%), 900 mbar
(equivalent CD_2 thickness ~11 mg/cm^2)

Fully identified channel
- PID
- Track reconstruction



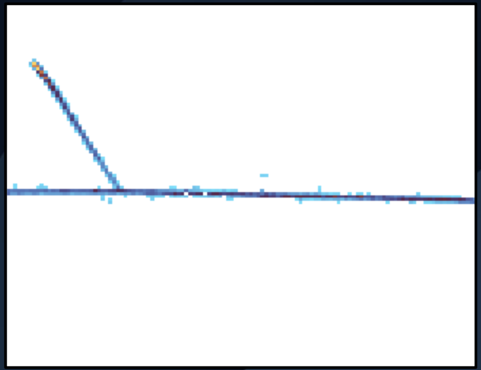
I. Blanco Calviño
PhD analysis, USC

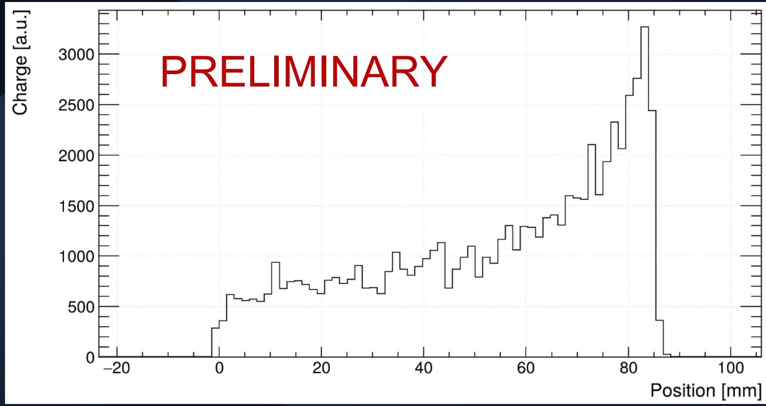
^{11}Li(d,p) with ACTAR-TPC at TRIUMF

I. Blanco Calviño
PhD analysis, USC

Particles stopping inside gas → charge profile

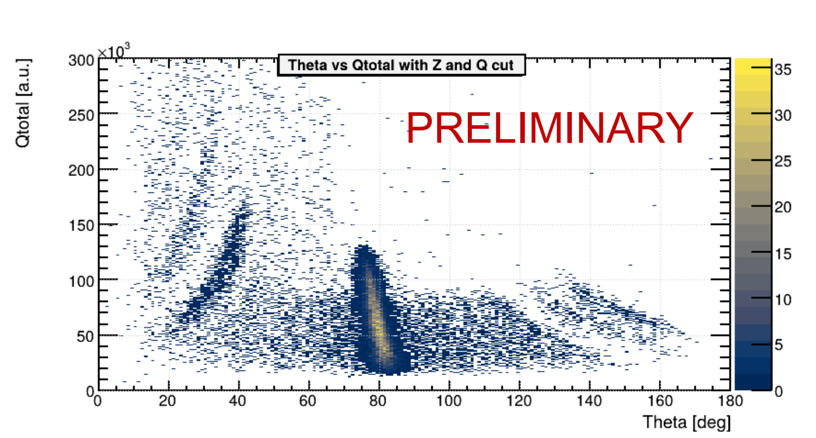
Pad trigger (“L1”)





→ Extended angular range and low energy particles

Work in progress...



^{11}Li(d,p) with ACTAR-TPC at TRIUMF

T. Roger
J. Pancin
M. Fisichella
C. Nicole

F. Delaunay
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A.M. Sanchez-Benítez

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S. Plante
Z. Sullivan

C. Andreoiu
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Y. Zhu

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J. Giovinazzo

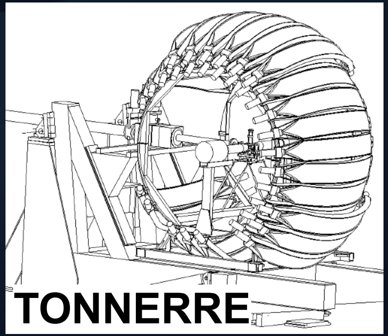
Rede CIGUS
Centros de investigación do Sistema Universitario de Galicia
Cofinanciado por la Unión Europea
Fondos Europeos

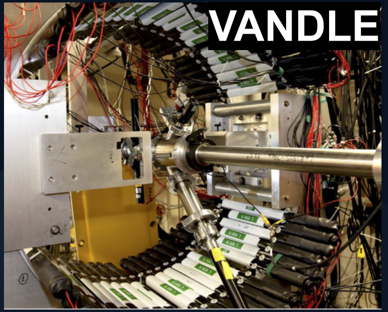
Beta-delayed neutron spectroscopy

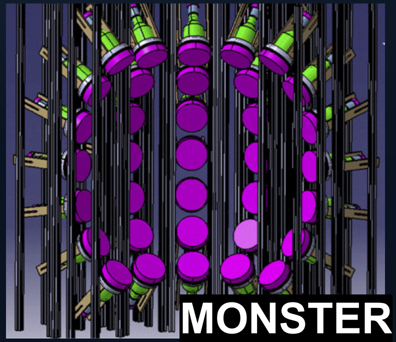
- β-decay of neutron-rich nuclei → neutron emission
  - Close to dripline: multi-neutron emission

- Modular arrays of thin organic scintillators
  - Time-of-flight spectroscopy
  - Multiple neutron detection possible but affected by cross-talk

- β-delayed neutron spectroscopy
  - R&D and characterization of organic scintillators with n-γ discrimination
  - Neutron cross-talk measurements at low energy
    → Extend multi-neutron detection to β-delayed neutrons
  - Study of multi-neutron emission in the β-decay of ^{11}Li



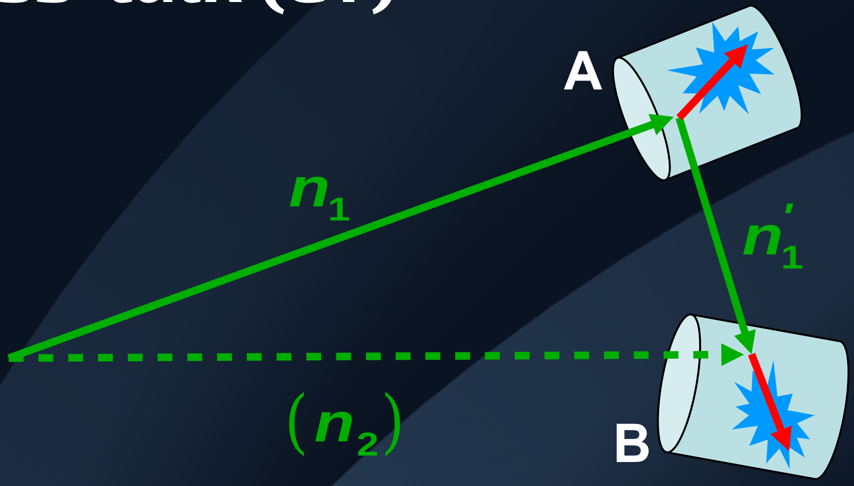




LPC CAEN

TONNERRE : NIM A 455, 412 / **VANDLE** : NIM A 836, 122 / **MONSTER** : JINST 7, C05012

Cross-talk (CT)



→ **Mimicks detection of 2 neutrons**

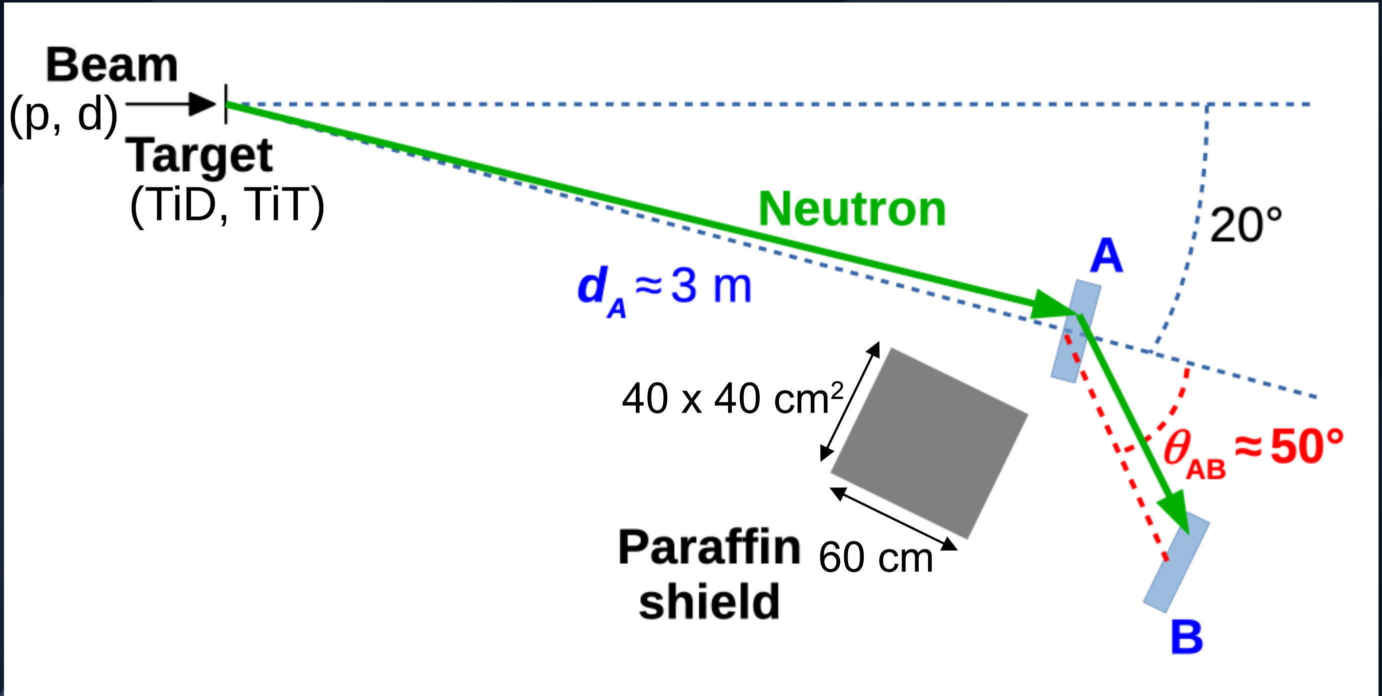
- Understanding CT crucial for array geometry, CT filters, simulations
- E_n < 10 MeV : lack of data

  → Measure CT between 2 liquid scintillator modules
  (cell = 20 cm diameter × 5 cm thickness, EDEN[1] and MONSTER[2] arrays)

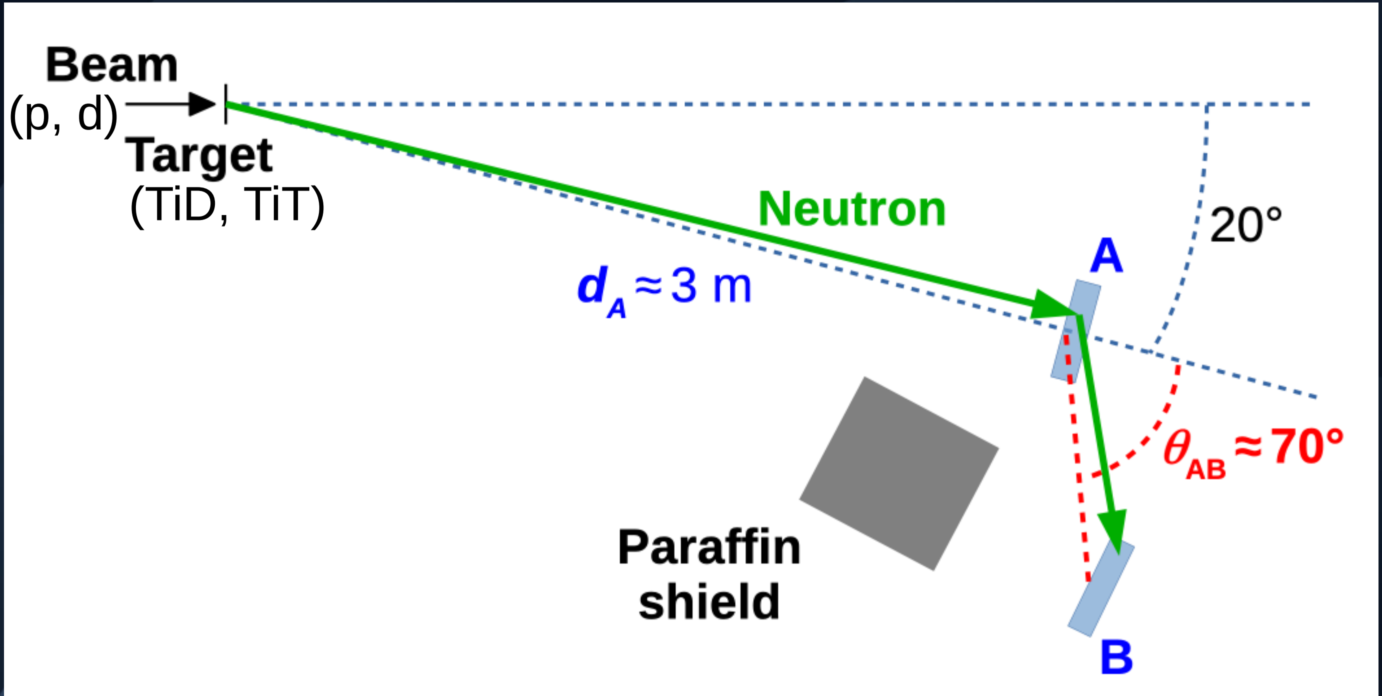
  → Monoenergetic neutrons, E_n = 1.4 to 15.5 MeV (CEA Arpajon, France)

[1] Laurent, NIM A 326, 517 [2] Garcia, JINST 7 C05012

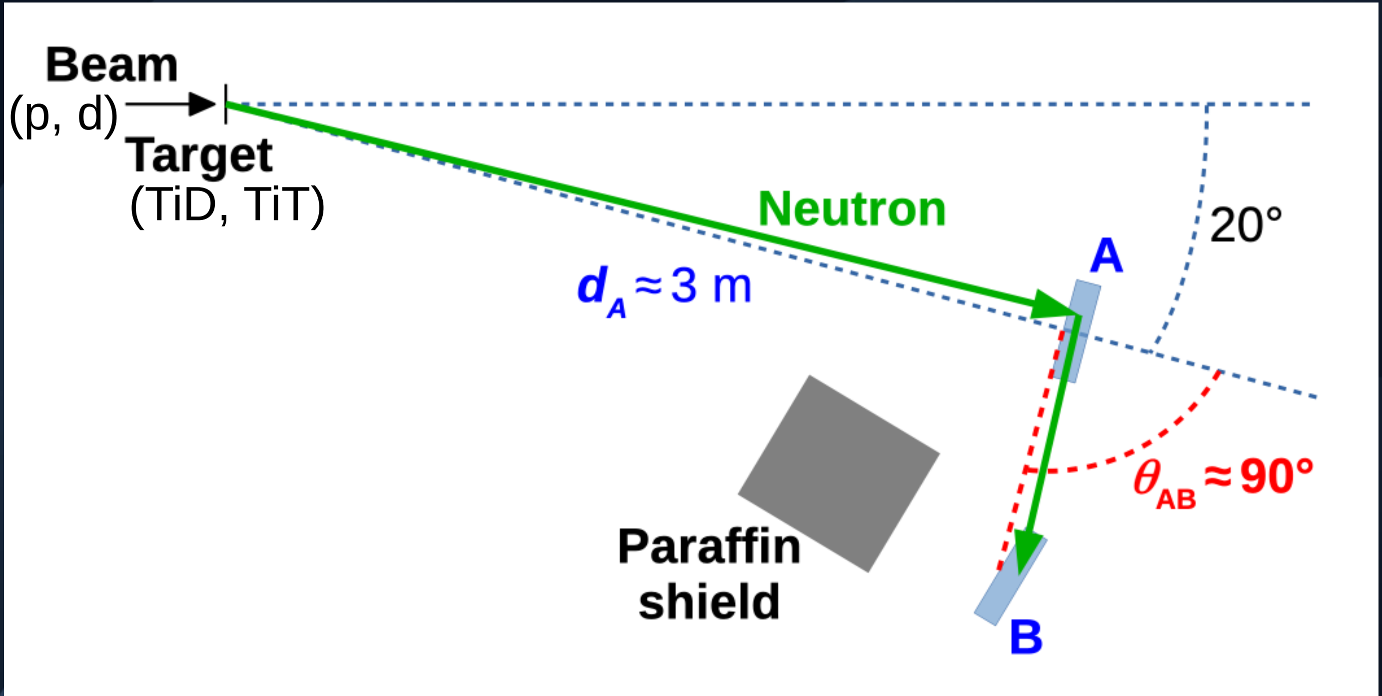
Detector placement



Detector placement



Detector placement



CT spectra & probabilities

$$P_{CT} = \frac{N_{CT}}{N_A}$$

- A+B coincidence
- n-γ discrimination → n hits

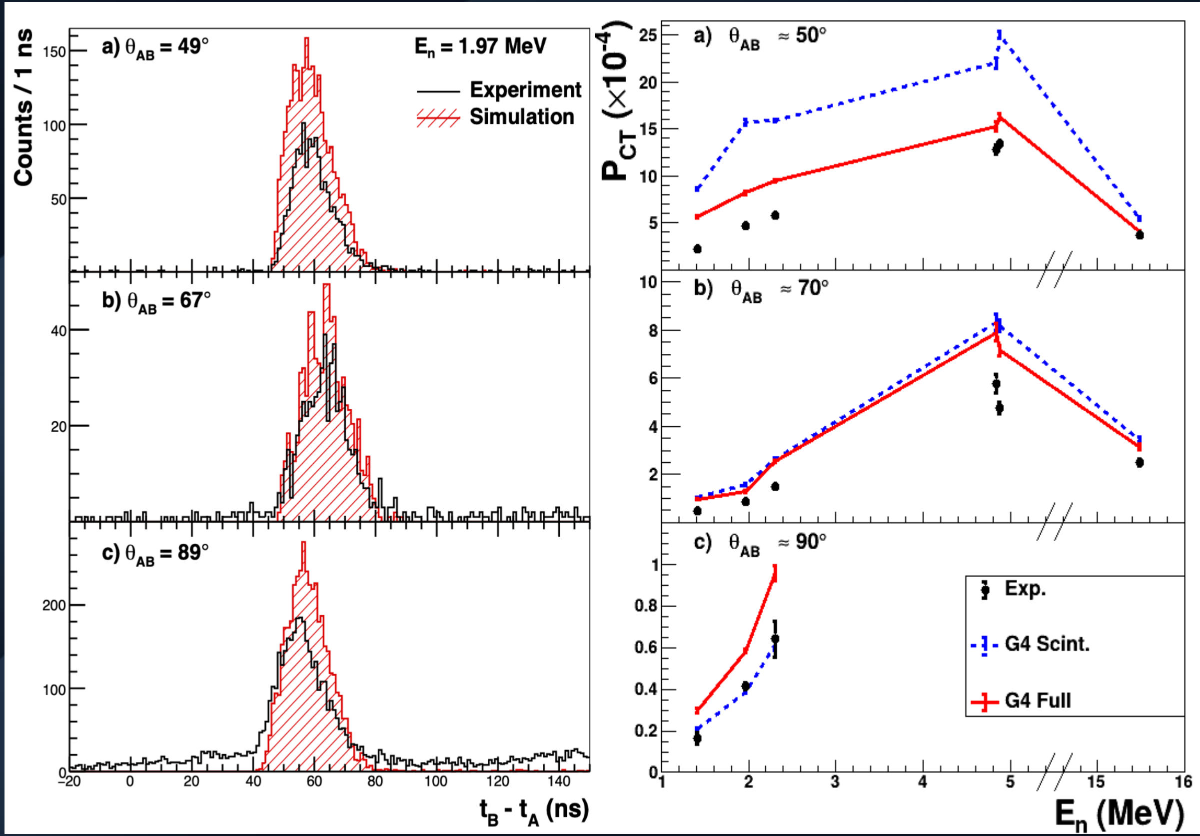
- **GEANT4 simulations**:
  - Scintillator only
  - Scintillator + inactive materials

→ CT time-of-flight well described

→ Evolution of P_{CT} with E_n and θ reasonably well described

→ P_{CT} overestimated

E_n = 2 MeV



Sénoville et al., NIM A 1075, 170370

Outlook

- **Nuclear structure far from stability with low-energy beams**

At TRIUMF/ARIEL :

- Transfer reactions with reaccelerated beams (~10 AMeV, ISAC II)
- β-delayed neutron spectroscopy with < 60 keV beams

- Fission fragments from e target station AETE (+ ISAC II)
- Neutron-rich lighter isotopes from p target station APTW (+ ISAC II)

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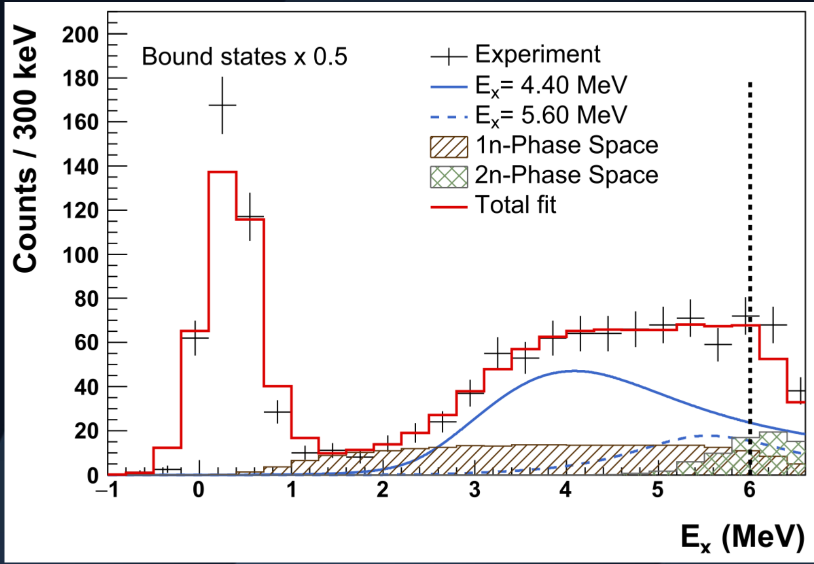
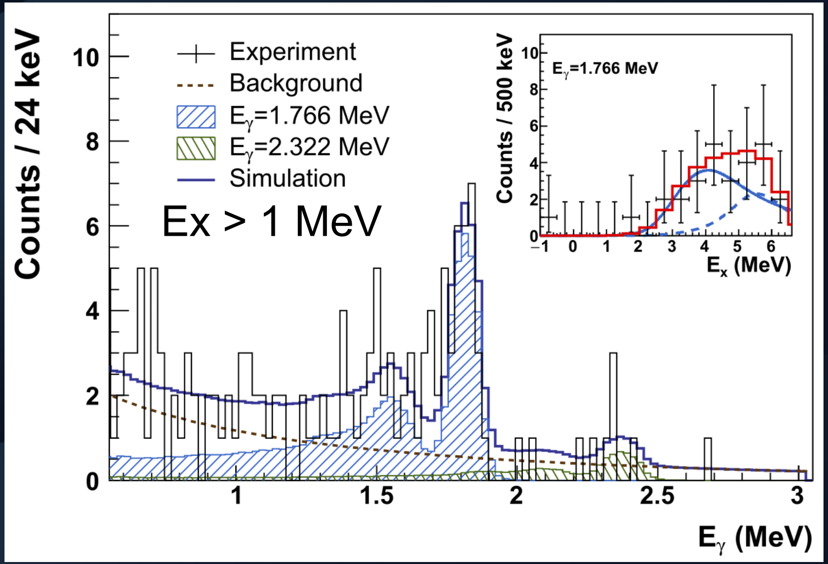
Thank you for your attention

Back up

$^{16}C(d,p)$ – ^{17}C unbound states

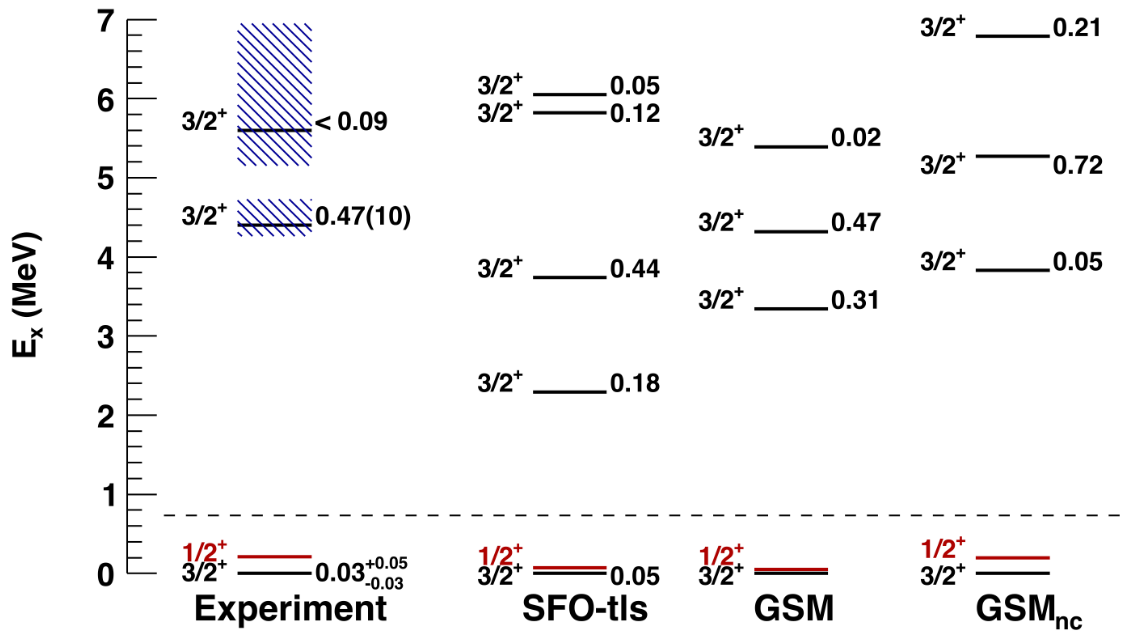
J. Lois-Fuentes, PhD USC
PLB 867, 139600





$^{16}C(d,p)$ – ^{17}C unbound states

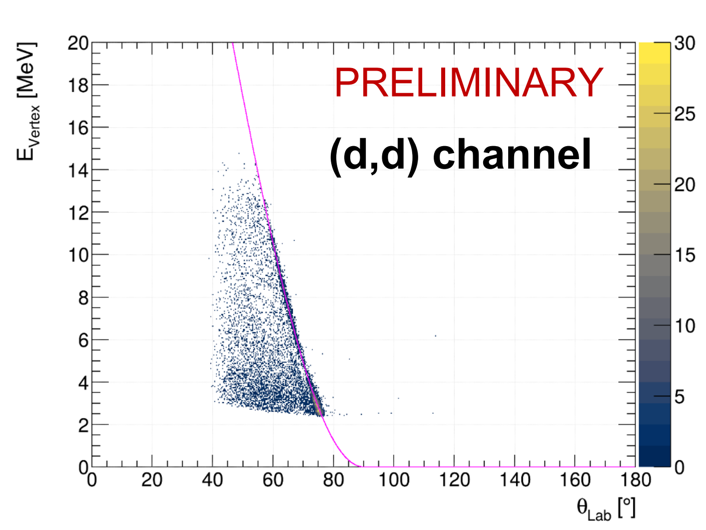
J. Lois-Fuentes, PhD USC
PLB 867, 139600

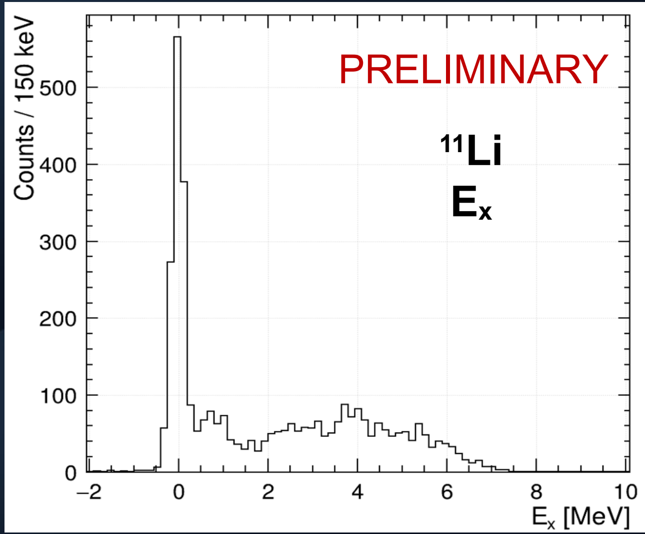


^{11}Li(d,p) with ACTAR-TPC at TRIUMF

I. Blanco Calviño
PhD analysis, USC

Si trigger





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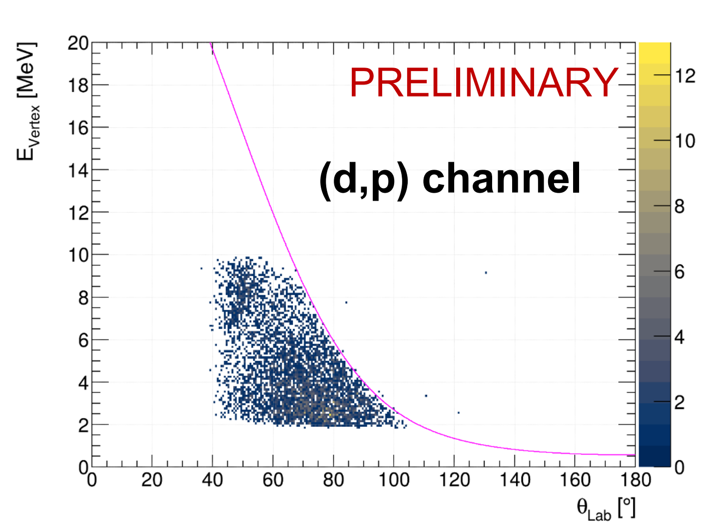
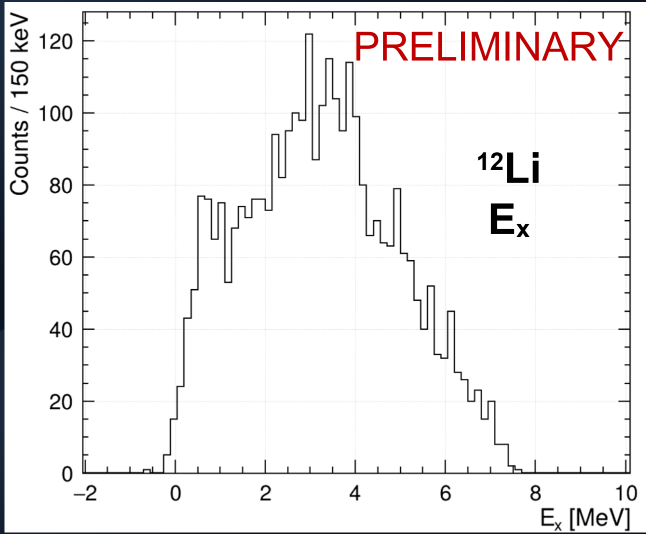
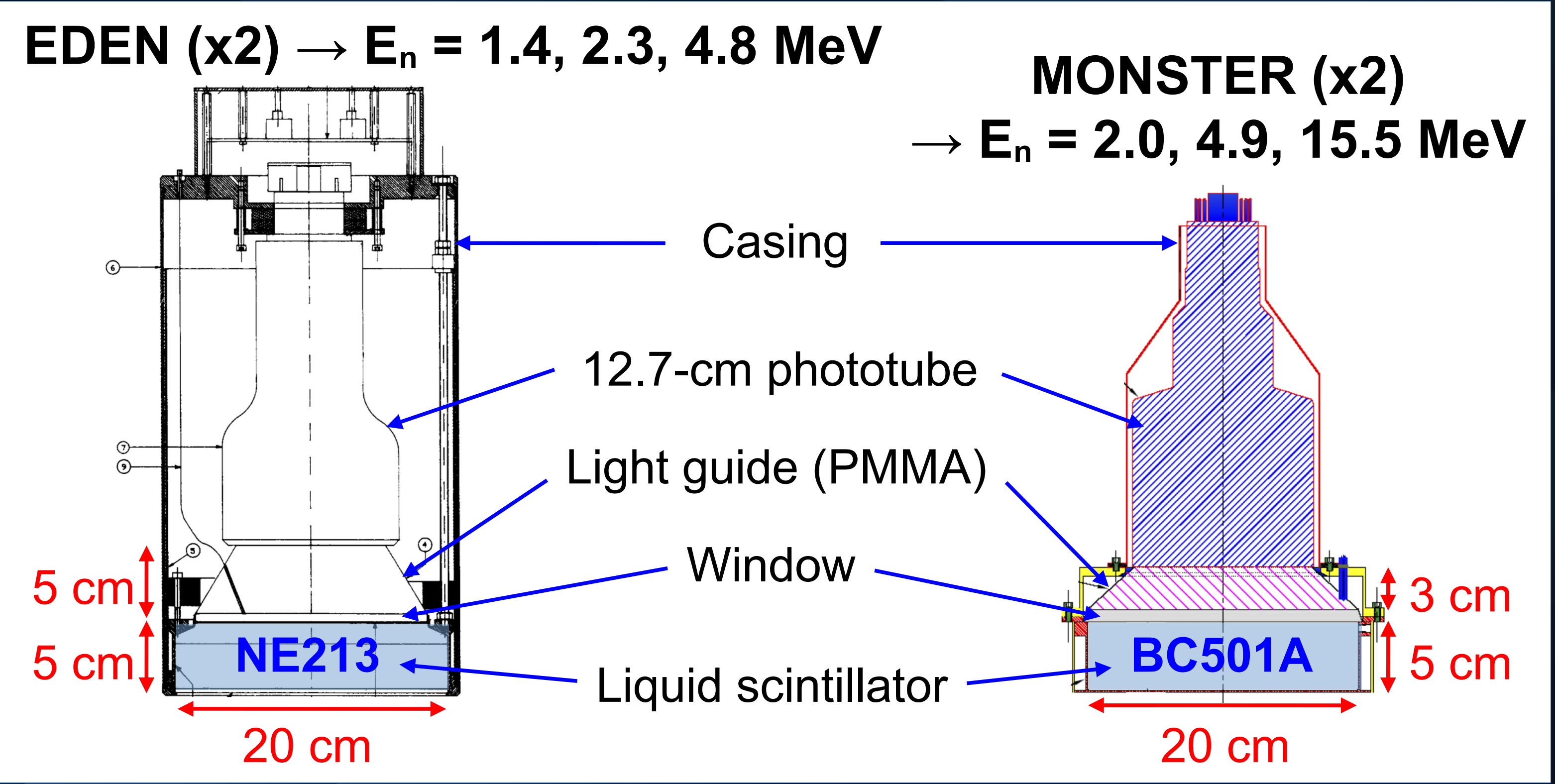




Detectors

- **Two series of measurements with two types of liquid scintillator modules**



Laurent, NIM A 326, 517
(IPN Orsay, KVI)

Garcia, JINST 7 C05012
(CIEMAT, IFIC, VECC...)

A→B TOF spectra : E_n = 1.4 & 2.0 MeV

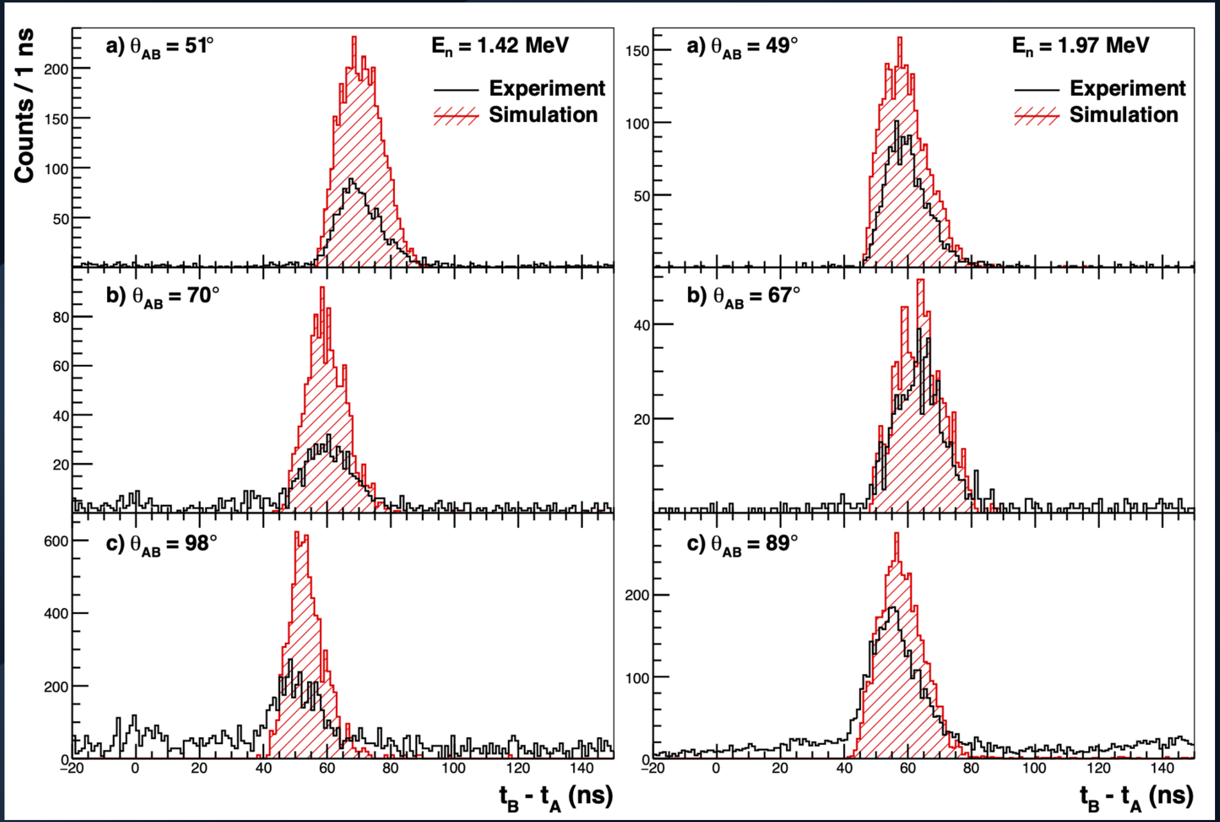
- A+B coincidence
- n-γ discrimination → neutron hits

- **GEANT4 simulations**

  Scintillator + inactive materials

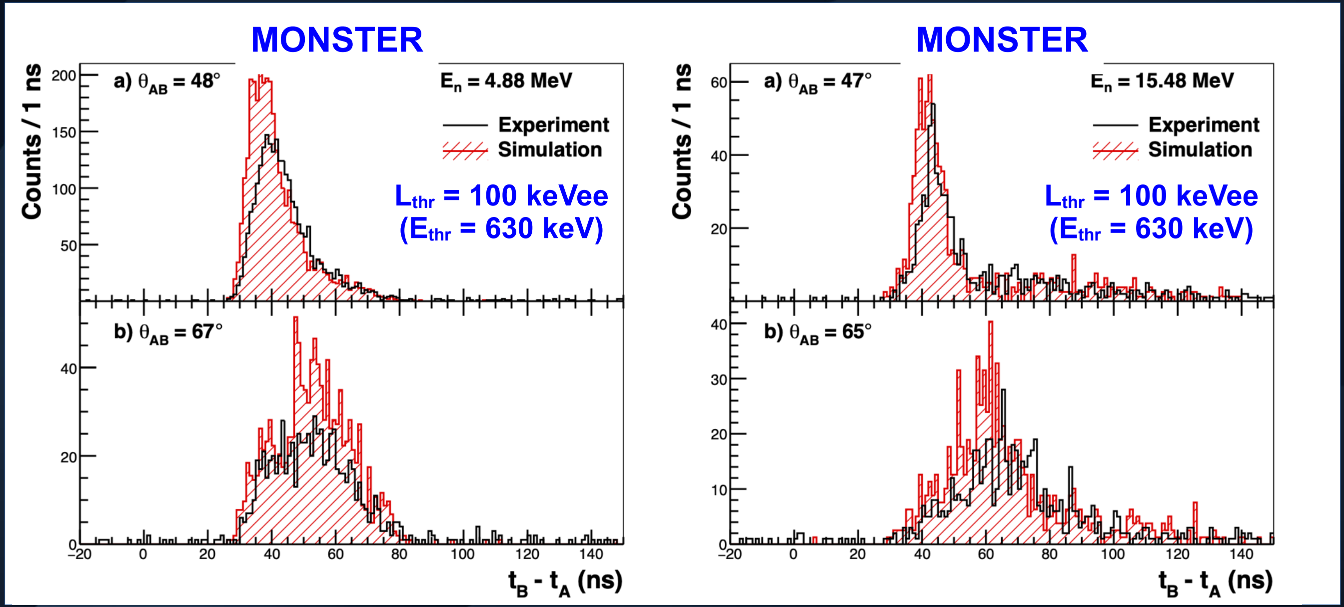
➢ **CT peak shape well described**

➢ **CT rates overestimated**



Sénoville et al., NIM A 1075, 170370

A→B TOF spectra : E_n = 4.9 & 15.5 MeV



- Broader, asymmetric peak → well described by simulations

Beams, targets and reactions

E_n (MeV) (20°, det. A)	Reaction	Beam energy (MeV)	Target	Impregnation ratio x	Thickness (mg/cm^2)
1.42	$T(p,n)^3He$	2.37	TiT_x	1.59	0.608
1.97	$T(p,n)^3He$	3.00	TiT_x	1.52	0.956
2.31	$T(p,n)^3He$	3.30	TiT_x	1.59	0.608
4.84	$D(d,n)^3He$	1.93	TiD_x	1.76	0.964
4.88	$D(d,n)^3He$	1.93	TiD_x	1.55	0.929
15.48	$T(d,n)^4He$	0.70	TiT_x	1.52	0.956

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Paraffin shield

- Cross section = 40 x 40 cm^2, thickness = 60 cm
- Reduce rate of real 2n coincidences from 2 reactions in the same beam pulse
- Simulations with MCNP (v4C2)

→ Transmission factor of neutrons with E_n'>600 keV (~threshold):

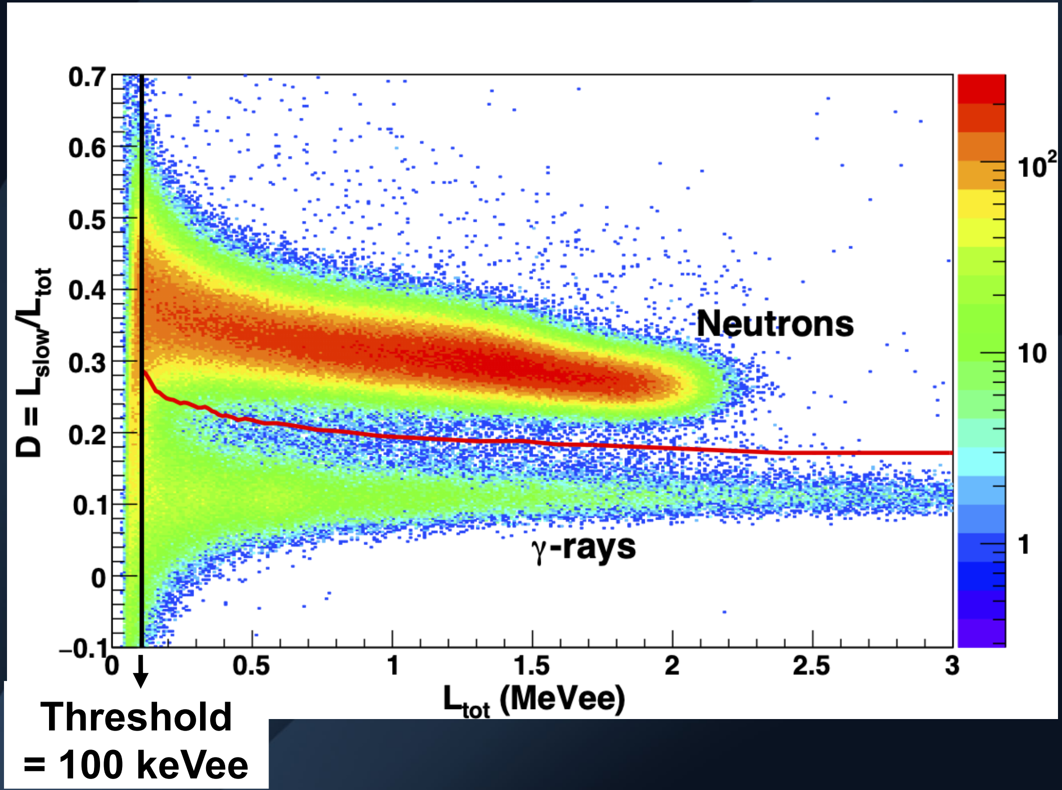
- E_n = 6 MeV : ~6 x 10^{-5}
- E_n = 16 MeV : ~5 x 10^{-3}

→ Given the beam intensities, the reaction cross sections, Poisson's statistics, detector solid angles, neutron efficiencies:

- P_{2n}/P_{CT} < 0.4 %

Pulse shape-discrimination

- E_n = 4.84 MeV, detector A (EDEN)



Integration windows:

- L_{tot} : 250 ns
- L_{slow} : delay = 40 ns

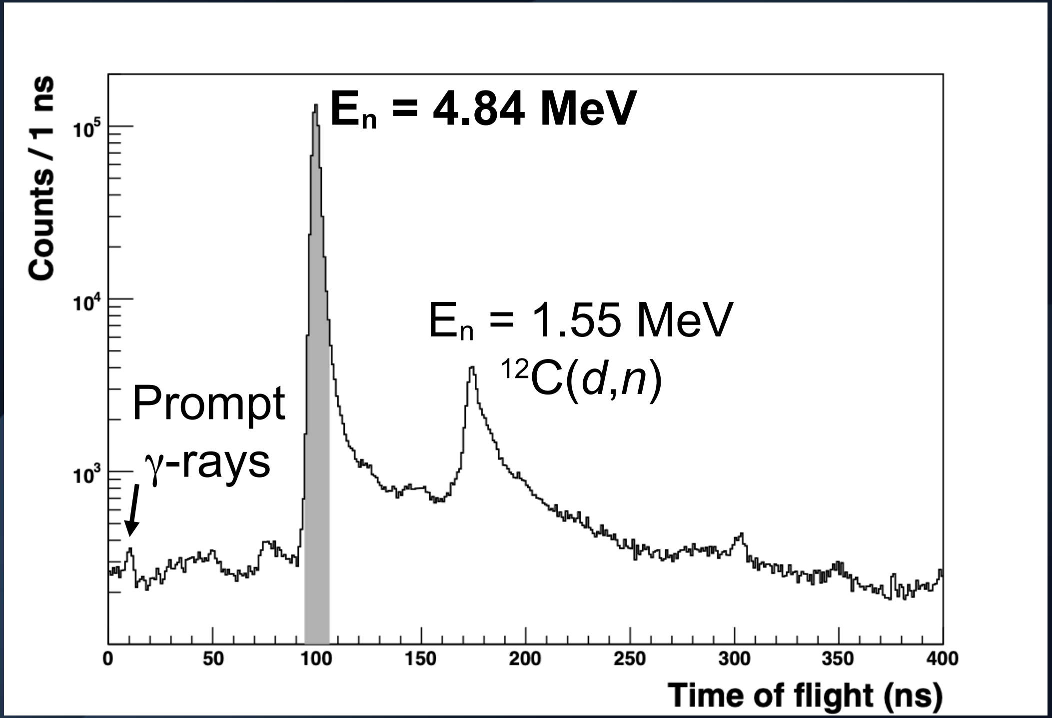
Figure of merit:

$$M = \frac{W_n - W_\gamma}{\overline{D_n} - \overline{D_\gamma}}$$

- M = 1.65 @ 1.0 MeVee
- M = 1.0 @ 0.23 MeVee

Detector A time-of-flight

- E_n = 4.84 MeV, detector A (EDEN)



Simulations

- GEANT4 v4.10.06
  - "Shielding" physics list: includes "NeutronHP" model for E_n<20 MeV → based on evaluated data (cross-section, energy-angle distributions)
  - Improved description of $^{12}C(n,\alpha)$ (E_n>6.2 MeV) and $^{12}C(n,n'3\alpha)$ (E_n>8.3 MeV) *
  - Light output response function for each charged particle type **
  - Same threshold on L_{tot} as in experimental data analysis
  - "Pulse shape discrimination" : if $L_{HCP} > 0.5 \times L_{tot}$ → neutron
- MENATE
  - n+p and n+^{12}C elastic scattering + important n+^{12}C reactions
  - Scintillator only

* Garcia, NIM A 868, 73

** Cecil, NIM 161, 439

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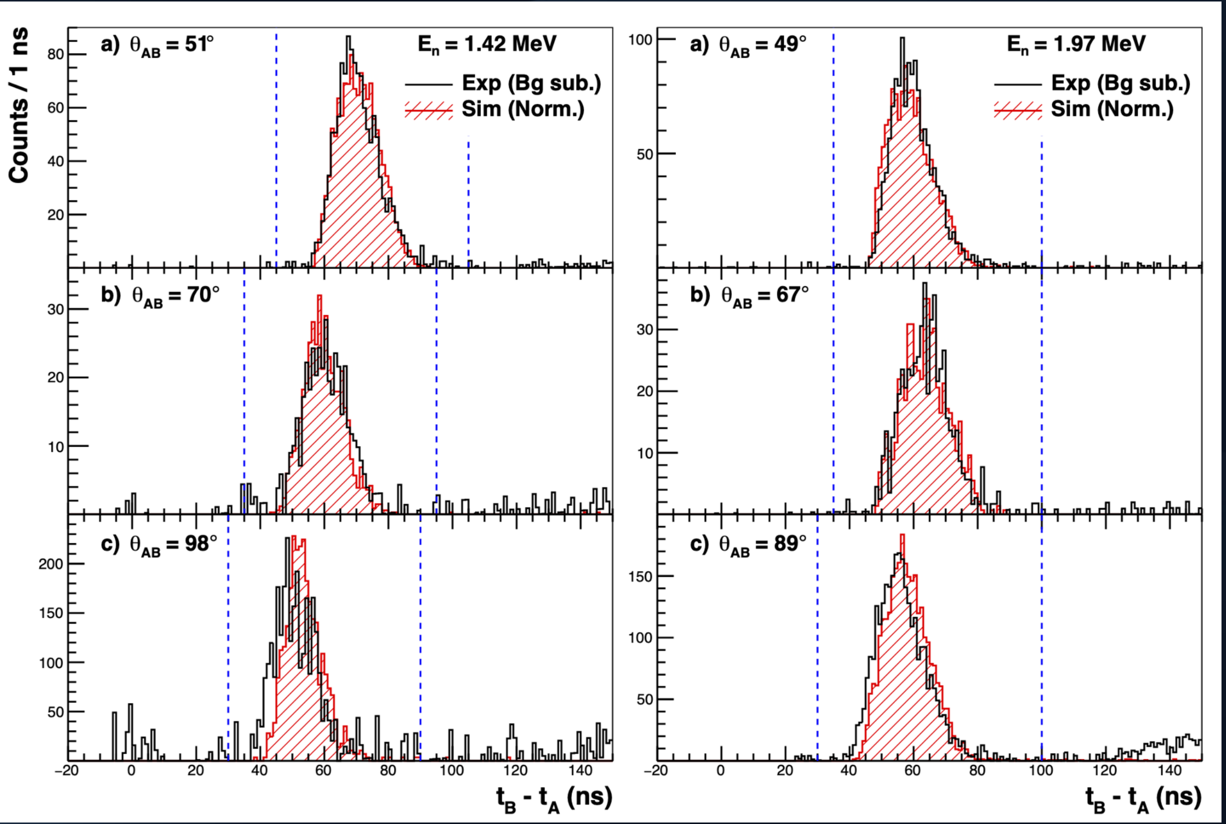
A→B TOF spectra : E_n = 1.4 & 2.0 MeV

- Experimental spectra:
  Background subtraction

- Simulations:
  Normalized to the same number of CT events as in the experiment



Cross-talk mechanisms

- np scattering = main *detection* process
- For ~90° and (1.42 MeV, ~70°):

  CT from single np scattering in A impossible

  → CT from multiple scattering in A

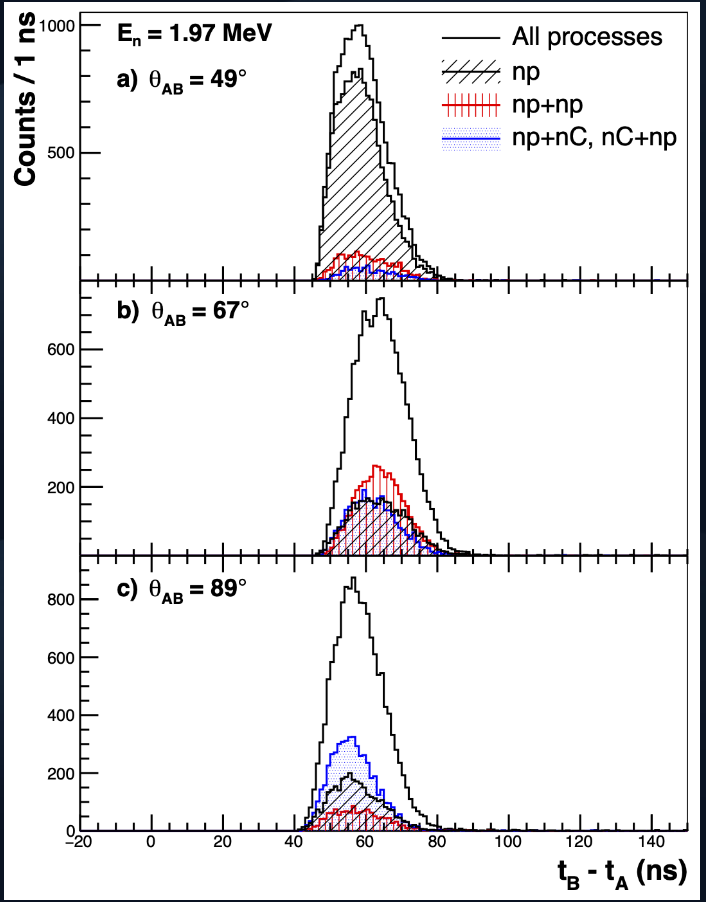
  or in A + light guide
- If CT from np scattering possible

  → Dominates CT

  → But other processes >20 % of CT
- CT identification algorithms for E_n<30 MeV:

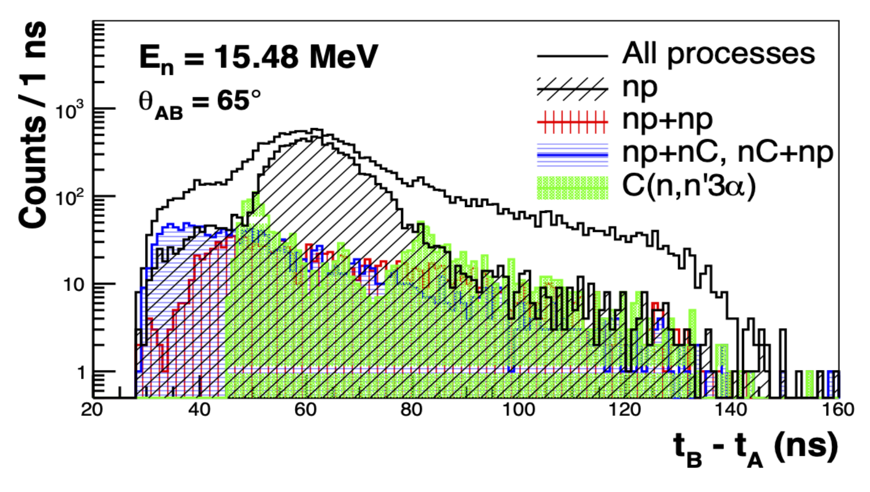
  → often assume np scattering in A

  → limited efficiency, need other criteria



Cross-talk mechanisms – E_n = 15.48 MeV

- When CT from single np kinematically possible → Dominates CT
- But other processes = significant source of CT (> 25 %)



- Single np scattering → 50-60 % of CT
- Double scattering → 17 % of CT
- $^{12}C(n,n'3\alpha)$ → 10 % of CT
- $^{12}C(n,\alpha)^{9}Be$, $^{12}C(n,p)^{12}B$, $^{12}C(n,d)^{11}B$ → no CT

- $t_B – t_A$ peak : single np scattering
- $^{12}C(n,n'3\alpha)$, double scattering → broader TOF distribution