Detector response functions for in situ high energy neutron spectrometry

Tanya Hutton

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DEPARTMENT OF PHYSICS
UNIVERSITY OF CAPE TOWN

n lab

MeASURe
Metrological and Applied Sciences University Research Unit

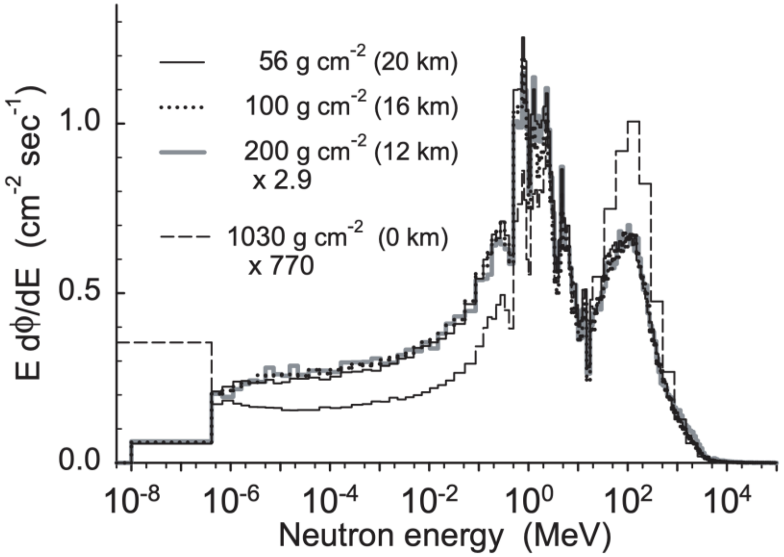
Joint IAEA–Consultative Committee for Ionizing Radiation Workshop on Neutron Beams at High Energy: Applications and Metrology

July 2025
Vienna, Austria

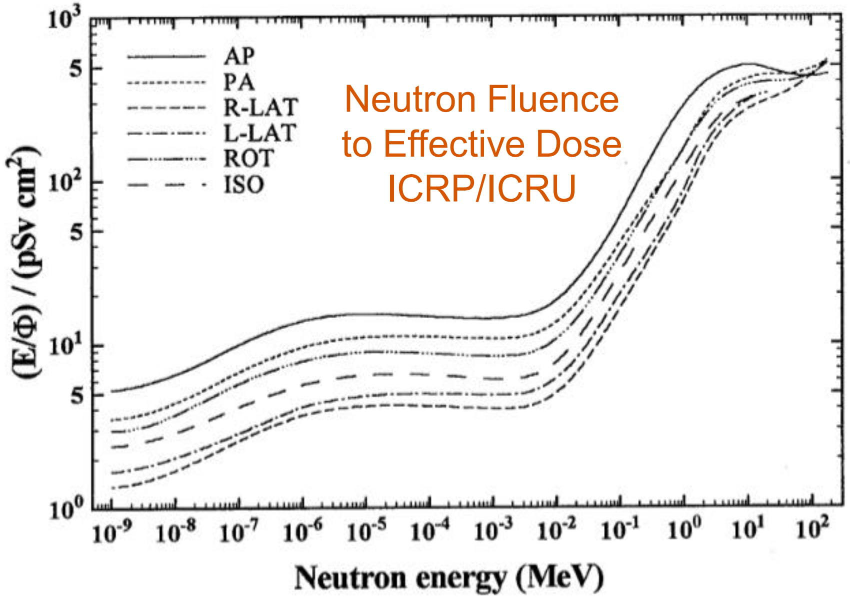
Why measure neutron spectra?

- Fast and high-energy neutrons occur in nuclear and medical accelerator facilities, nuclear reactors, aviation, space, etc.
- Different applications require different quantities: H*(10), fluence, kerma, etc.
- Require knowledge of energy spectrum, fluence and spatial distribution.

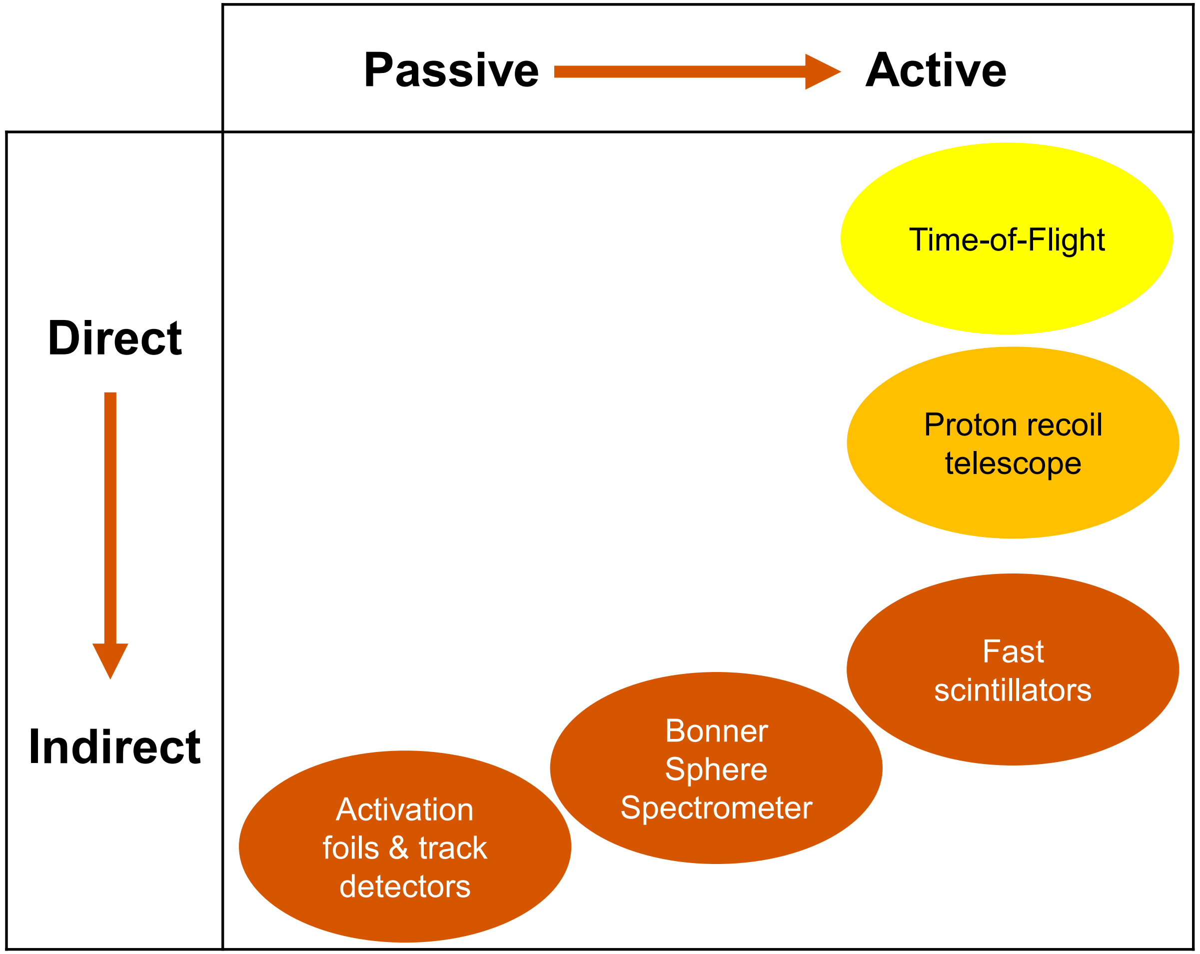
Understanding radiation risk requires **precise knowledge of the radiation field in each environment** to calculate the radiation exposure in different scenarios and validate models to assess the relevant risks.

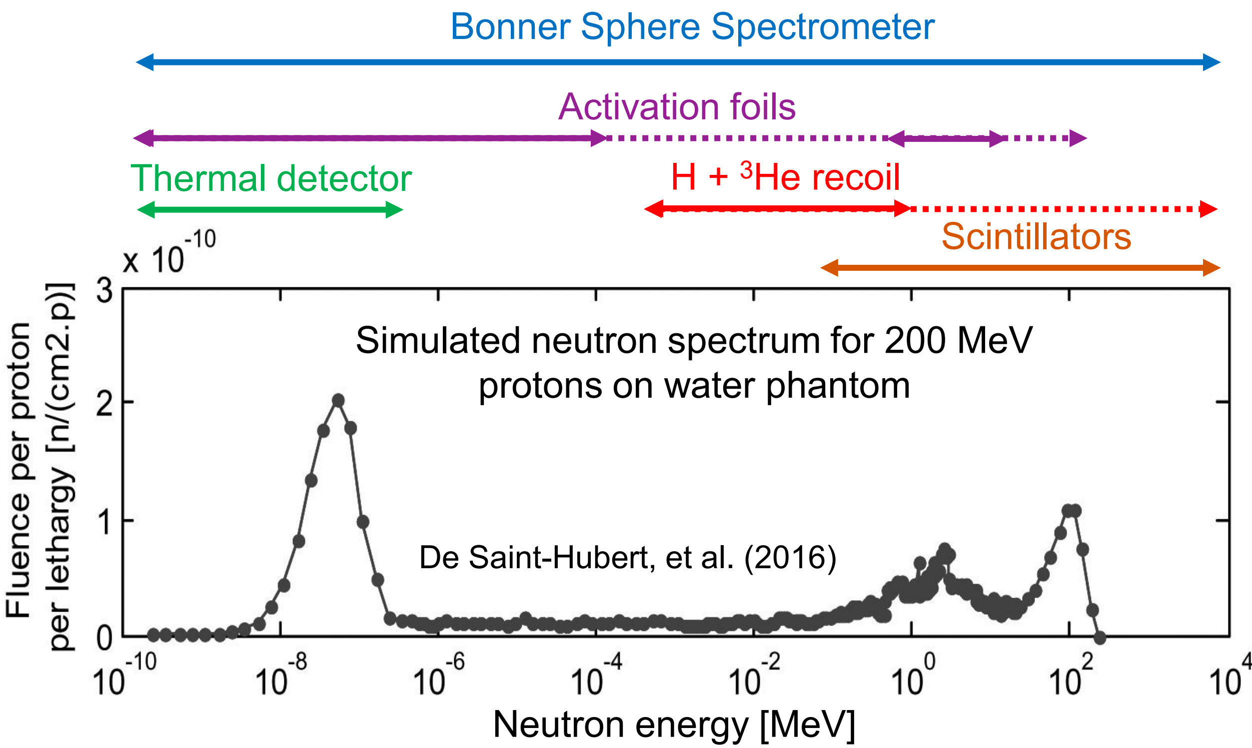


Goldhagen, et al. (2004)



Detector systems for spectrometry





Reference Standards: Instrumentation
Session

13:30-14:05 **Instruments for the characterization of high energy neutron beams**

Speaker
Ralf Nolte

Detector response functions must:

… cover the full energy and fluence range of interest to the application;

… be calibrated to both energy and fluence, with a known uncertainty;

… and be traceable to reference standards.

Spectrum unfolding

Measured neutron pulse height spectrum (bin *i*)

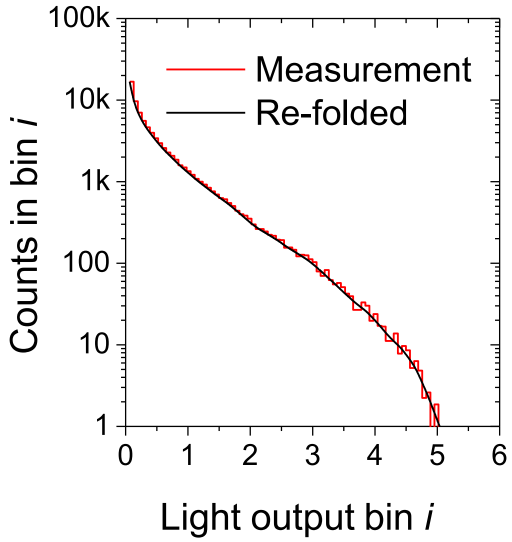
Detector response matrix

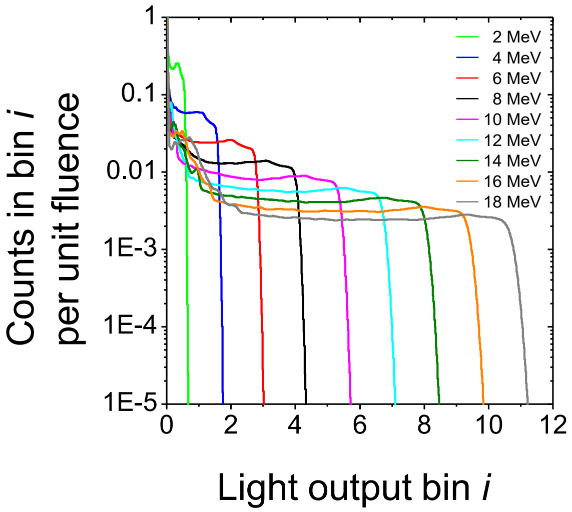
$$z_i = \sum_j R_{ij}\phi_j$$

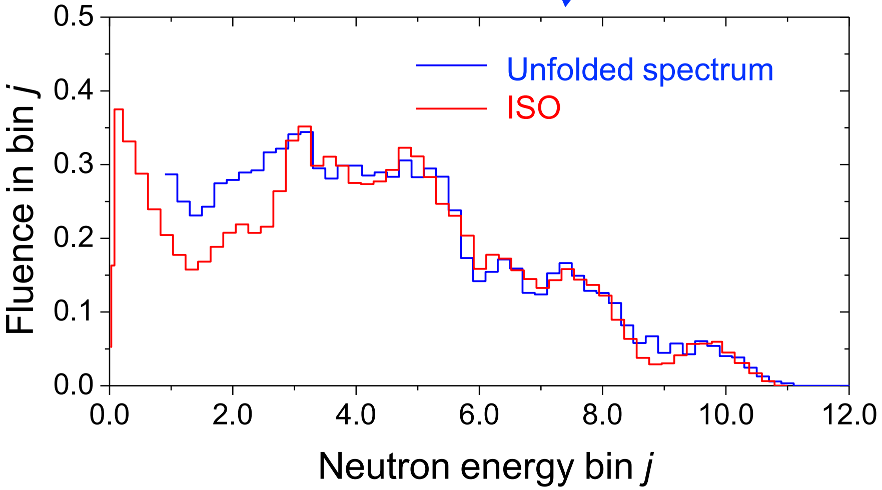
Solution spectrum (bin *j*)

Solution spectrum obtained using unfolding algorithm:

- Iterative: SAND-II, GRAVEL
- Maximum likelihood: MAXED, FRUIT
- Bayesian inference: WinBUGS, PyMC
- Machine learning, etc.







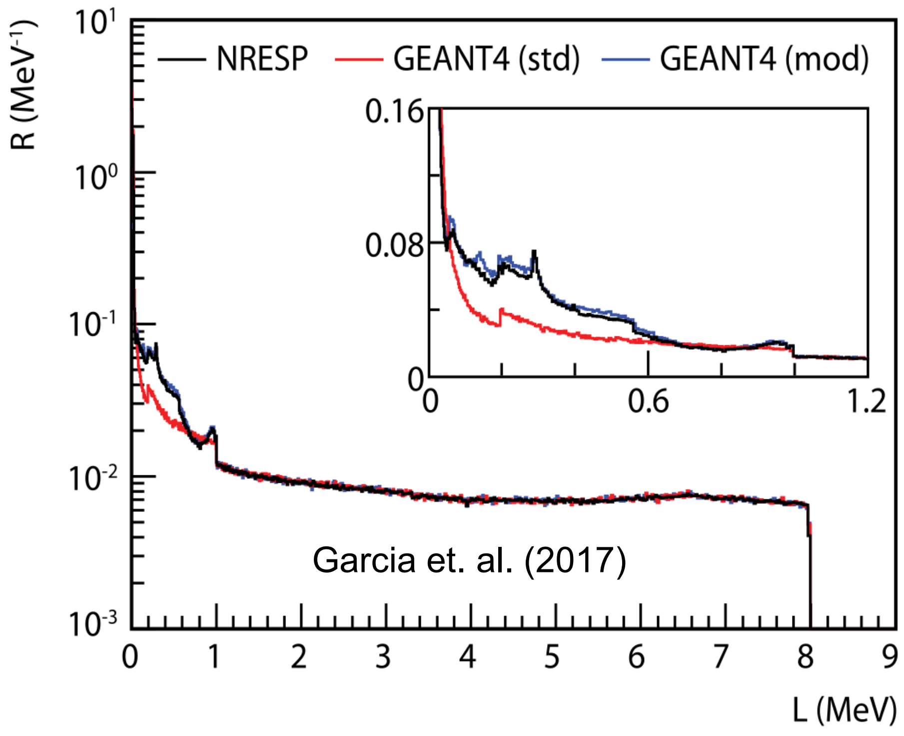
All algorithms rely on accurate and well-characterised detector response functions.

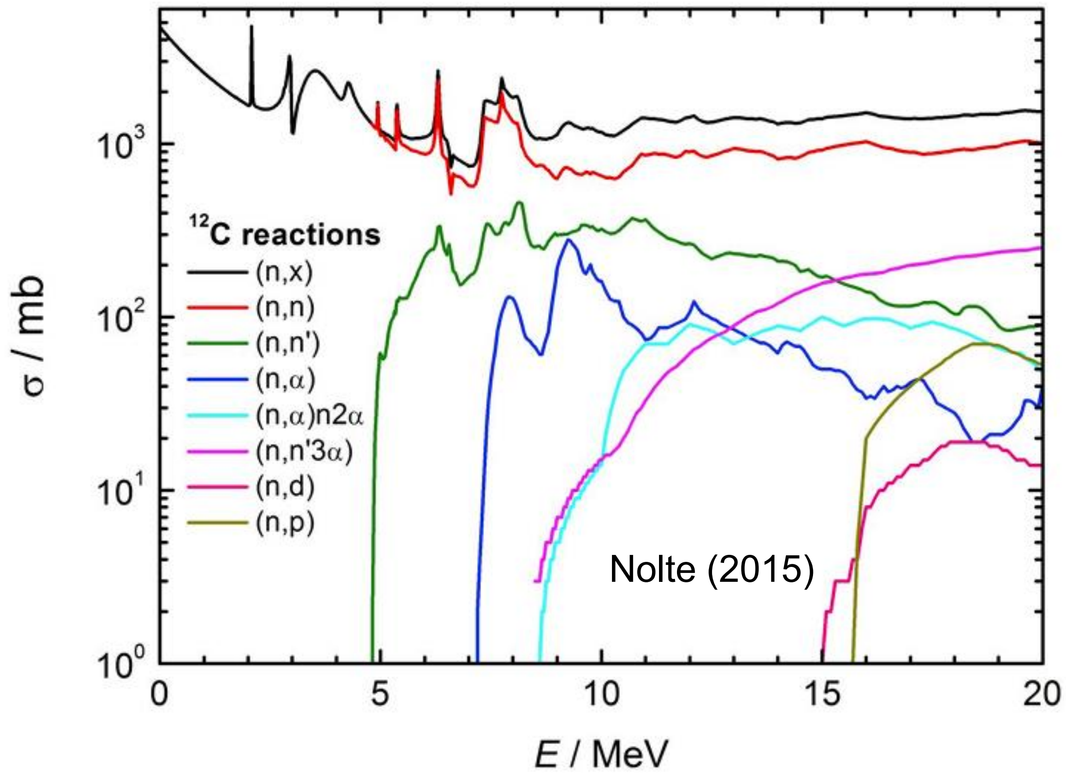
$E_n < 20$ MeV

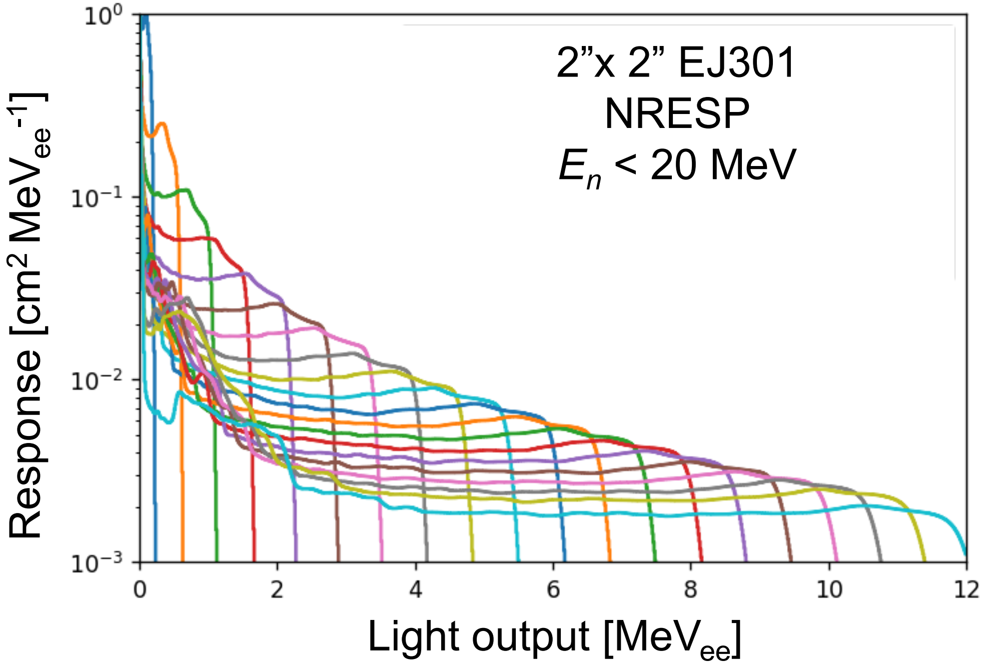
Detector response can be reliably simulated using:

- general purpose radiation transport codes MCNP, FLUKA, GEANT4, …
- dedicated codes NRESP, SCINFUL, CECiL…

… subject to experimental validation



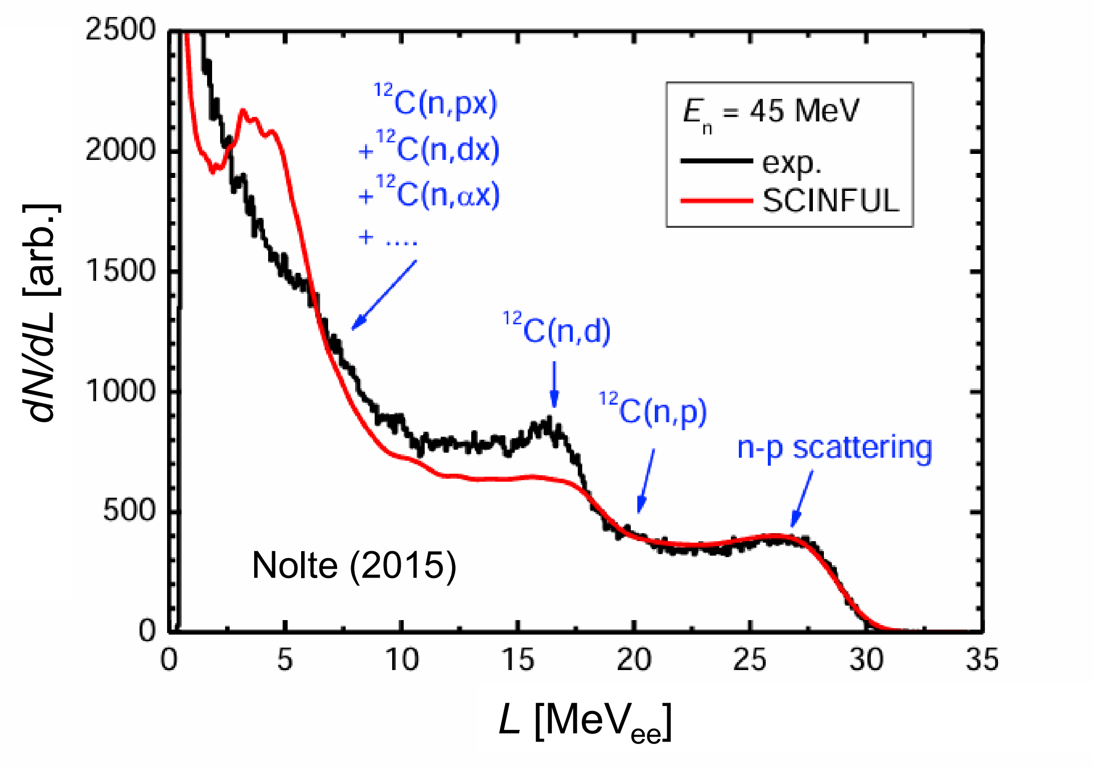


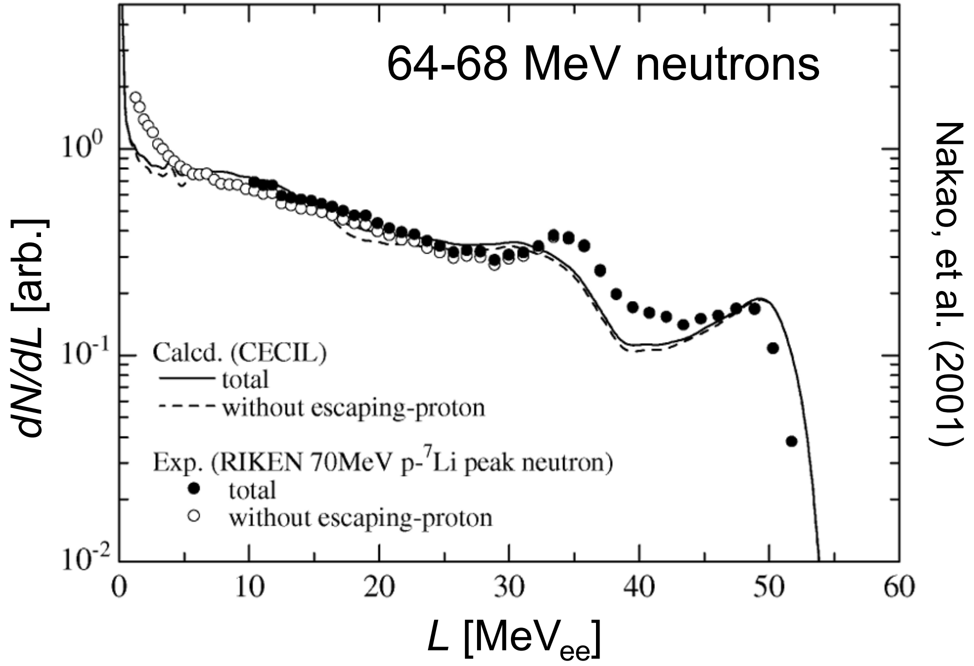


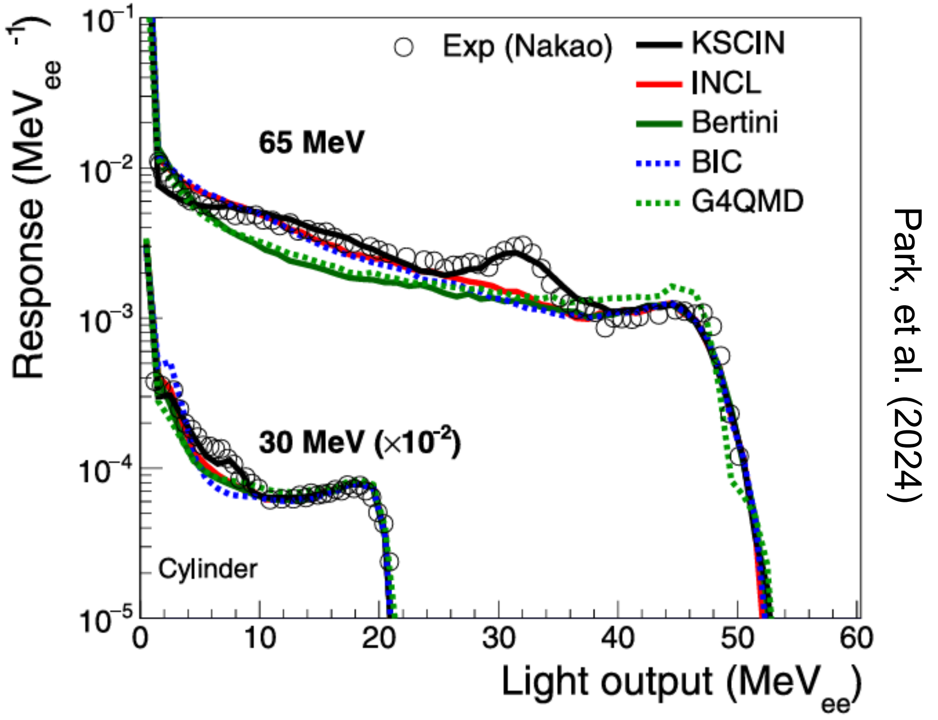
E_n > 20 MeV

Simulation not generally considered reliable above 20 MeV

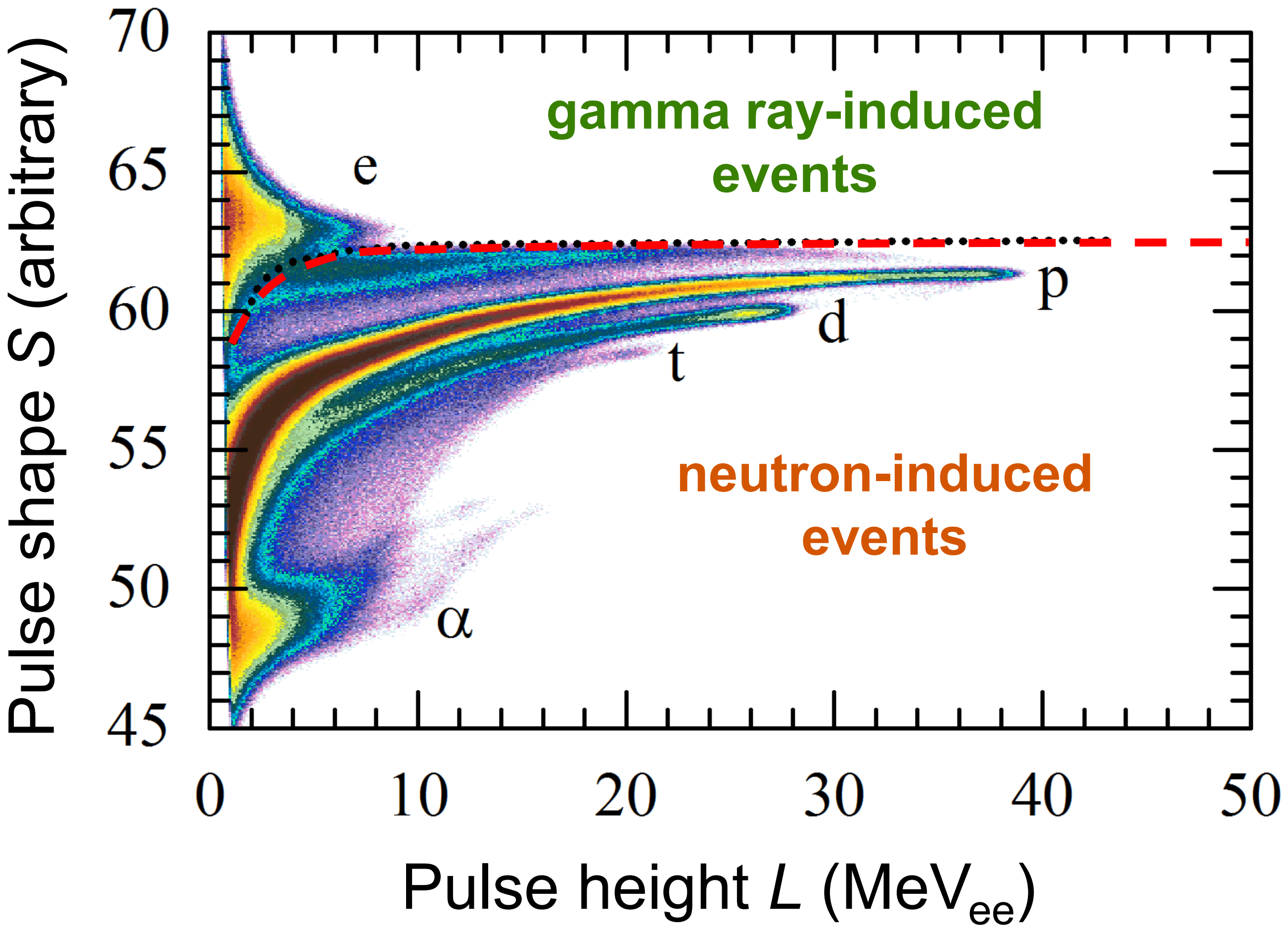
General purpose radiation transport codes rely on mostly unvalidated nuclear models for reactions







Neutrons and gamma rays produced by a 66 MeV proton beam irradiating a 6.0 mm Li target, measured with a 2” x 4” BC-501A detector



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Neutron reactions on ^{12}C at 90 MeV

production of carbon isotopes

- ^{12}C (n;n) ^{12}C
- ^{12}C (n;3n) ^{12}C
- ^{12}C (n;2n) ^{12}C

production of boron isotopes

- ^{12}C (n;p) ^{12}B
- ^{12}C (n;p,2n) ^{10}B
- ^{12}C (n;d) ^{11}B
- ^{12}C (n;p,d,3n) ^{8}B
- ^{12}C (n;t,2n) ^{8}B
- ^{12}C (n;p,n) ^{11}B
- ^{12}C (n;p,4n) ^{8}B
- ^{12}C (n;d,n) ^{10}B
- ^{12}C (n;t) ^{10}B

production of beryllium isotopes

- ^{12}C (n;2p,n) ^{10}Be
- ^{12}C (n;2p,4n) ^{7}Be
- ^{12}C (n;d,p,n) ^{9}Be
- ^{12}C (n;2d) ^{9}Be
- ^{12}C (n;t,p) ^{9}Be
- ^{12}C (n;t,d,n) ^{7}Be
- ^{12}C (n;α,2n) ^{7}Be
- ^{12}C (n;2p,2n) ^{9}Be
- ^{12}C (n;d,p) ^{10}Be
- ^{12}C (n;d,p,3n) ^{7}Be
- ^{12}C (n;2d,2n) ^{7}Be
- ^{12}C (n;t,p,2n) ^{7}Be
- ^{12}C (n;α) ^{9}Be

production of Be* → 2α

- ^{12}C (n;α,n) 2α
- ^{12}C (n;2p,3n) 2α
- ^{12}C (n;p,2d,n) 2α
- ^{12}C (n;d,t) 2α
- ^{12}C (n;^{3}He,2n) 2α
- ^{12}C (n;p,d,2n) 2α
- ^{12}C (n;p,t,n) 2α

production of lithium isotopes

- ^{12}C (n;3p,n) ^{9}Li
- ^{12}C (n;3p,3n) ^{7}Li
- ^{12}C (n;p,^{3}He) ^{9}Li
- ^{12}C (n;p,^{3}He,2n) ^{7}Li
- ^{12}C (n;p,α) ^{8}Li
- ^{12}C (n;p,α,2n) ^{6}Li
- ^{12}C (n;d,^{3}He,n) ^{7}Li
- ^{12}C (n;2p,d) ^{9}Li
- ^{12}C (n;2p,d,2n) ^{7}Li
- ^{12}C (n;p,2d) ^{8}Li
- ^{12}C (n;p,2d,2n) ^{6}Li
- ^{12}C (n;d,α,n) ^{6}Li
- ^{12}C (n;t,^{3}He,n) ^{6}Li
- ^{12}C (n;3d) ^{7}Li
- ^{12}C (n;p,d,t,n) ^{6}Li
- ^{12}C (n;^{6}Li,n) ^{7}Li
- ^{12}C (n;2d,t) ^{6}Li
- ^{12}C (n;3p,2n) ^{8}Li
- ^{12}C (n;3p,4n) ^{6}Li
- ^{12}C (n;p,^{3}He,n) ^{8}Li
- ^{12}C (n;p,^{3}He,3n) ^{6}Li
- ^{12}C (n;p,α,n) ^{7}Li
- ^{12}C (n;d,^{3}He) ^{8}Li
- ^{12}C (n;d,^{3}He,2n) ^{6}Li
- ^{12}C (n;2p,d,n) ^{8}Li
- ^{12}C (n;2p,d,3n) ^{6}Li
- ^{12}C (n;p,2d,n) ^{7}Li
- ^{12}C (n;d,α) ^{7}Li
- ^{12}C (n;t,^{3}He) ^{7}Li
- ^{12}C (n;3d) ^{7}Li
- ^{12}C (n;p,d,t) ^{7}Li
- ^{12}C (n;^{6}Li) ^{7}Li
- ^{12}C (n;t,α) ^{6}Li

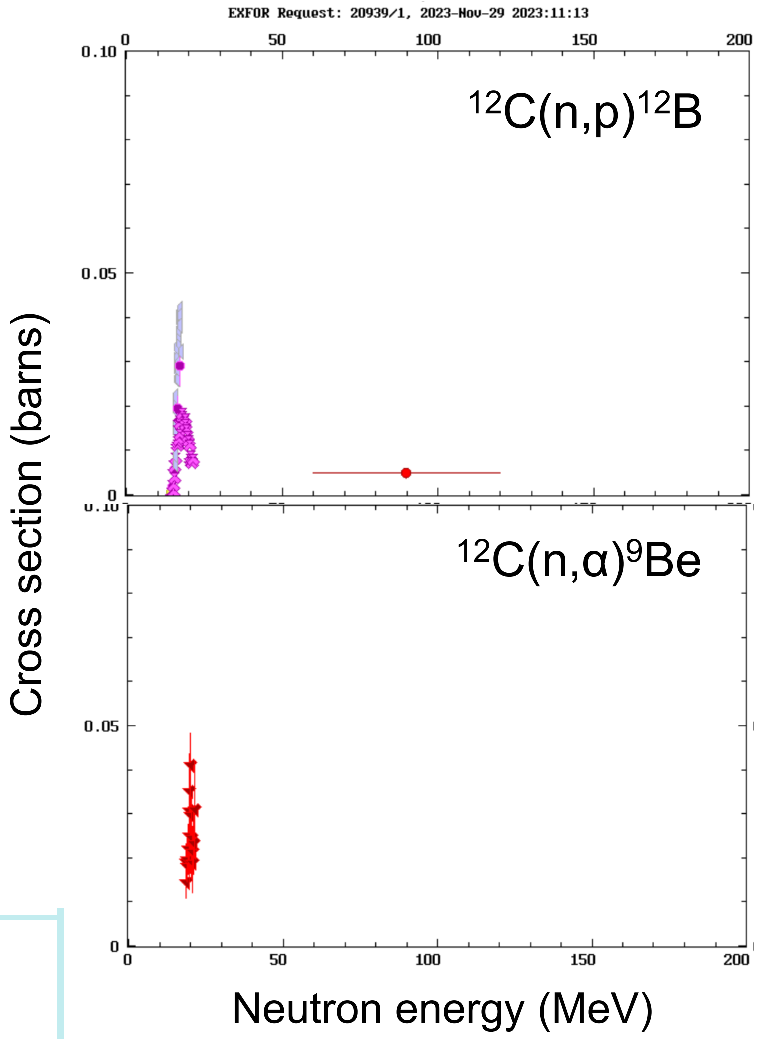
[Kellogg (1956)]

16:15-16:30

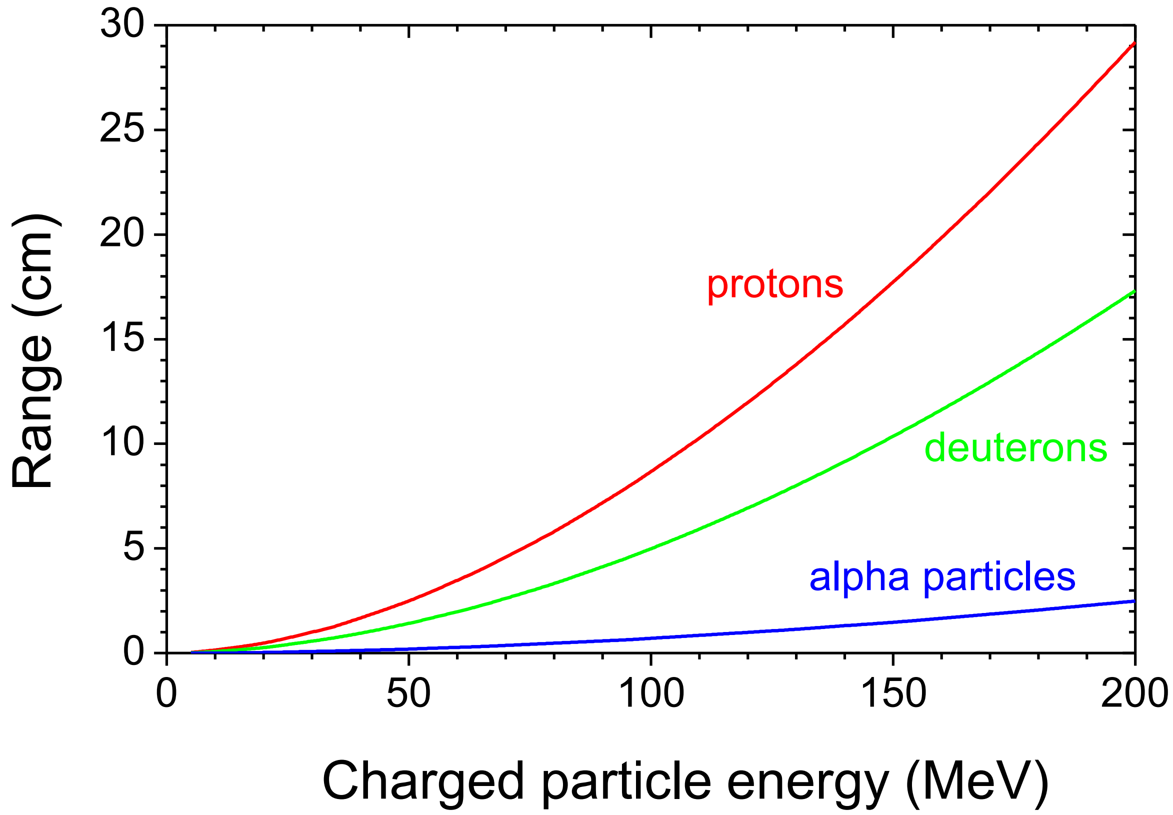
EURADOS task on improving the description of nuclear reactions between nucleons and light nuclei, notably 12C, 14N and 16O

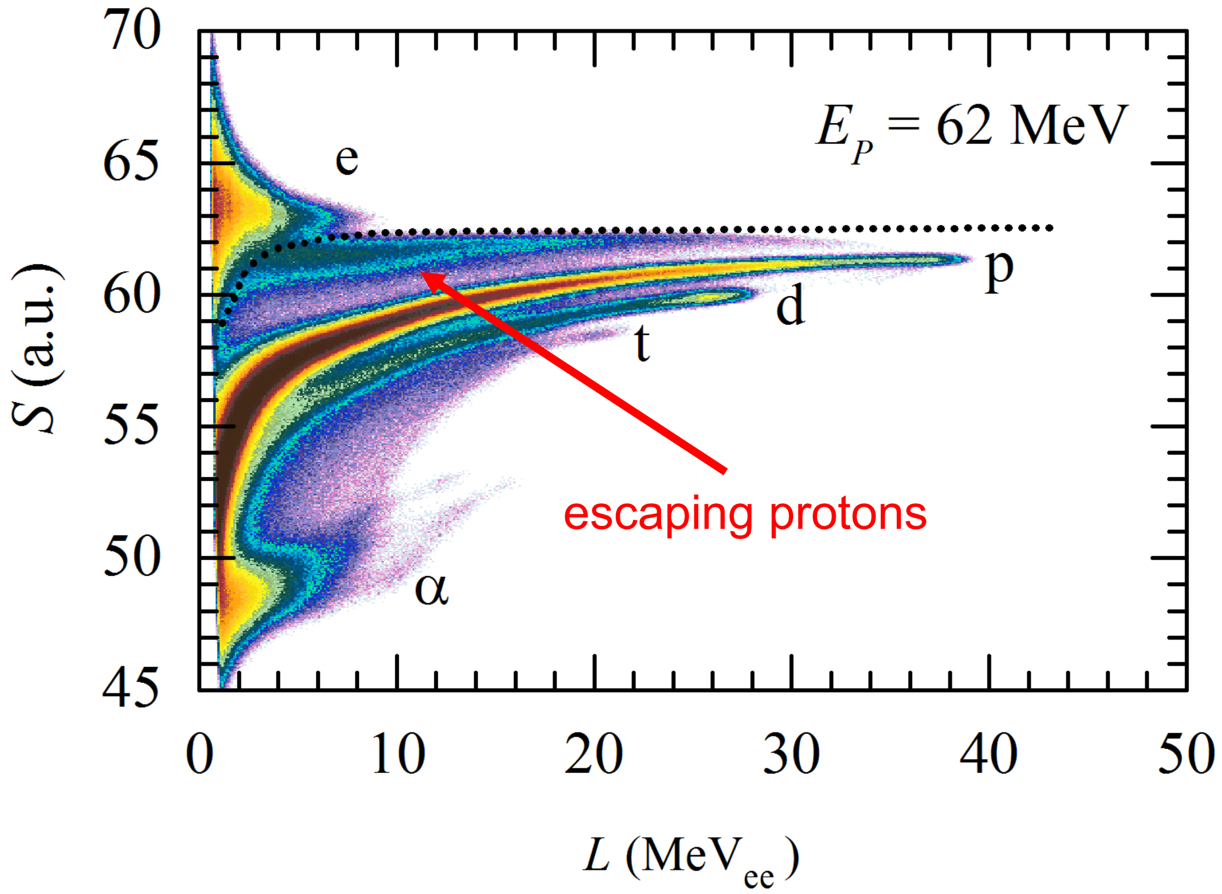
Speaker

Michaël Petit



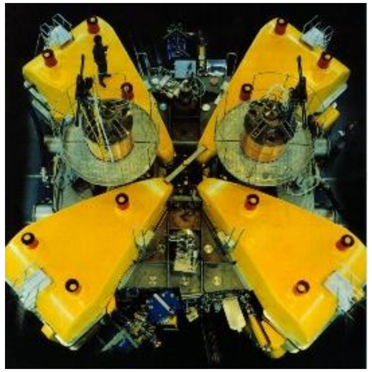
Range of charged particles in BC-501A



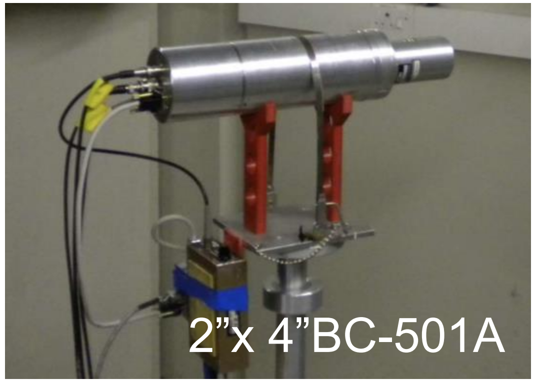


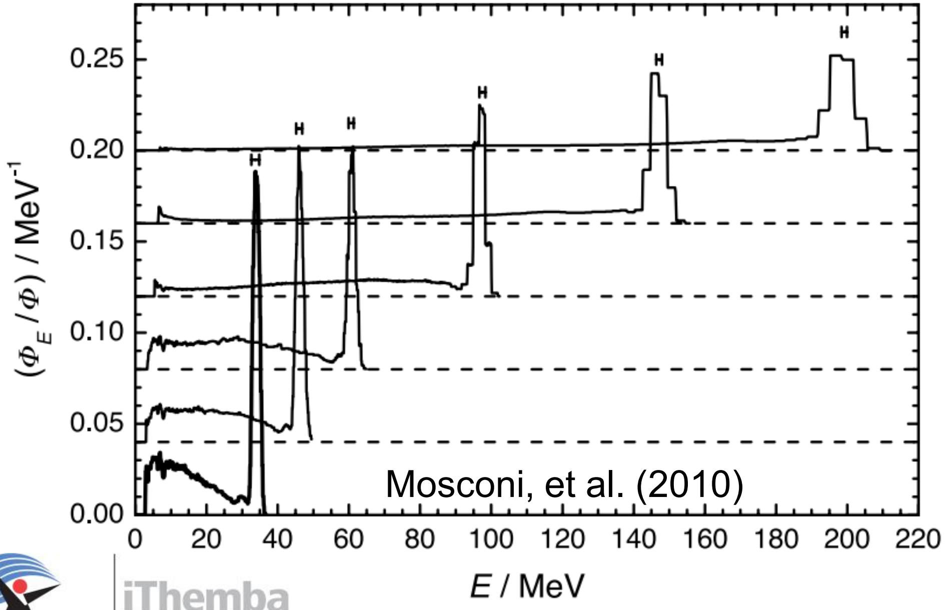
… detector response must be <u>measured</u> for accurate unfolding…

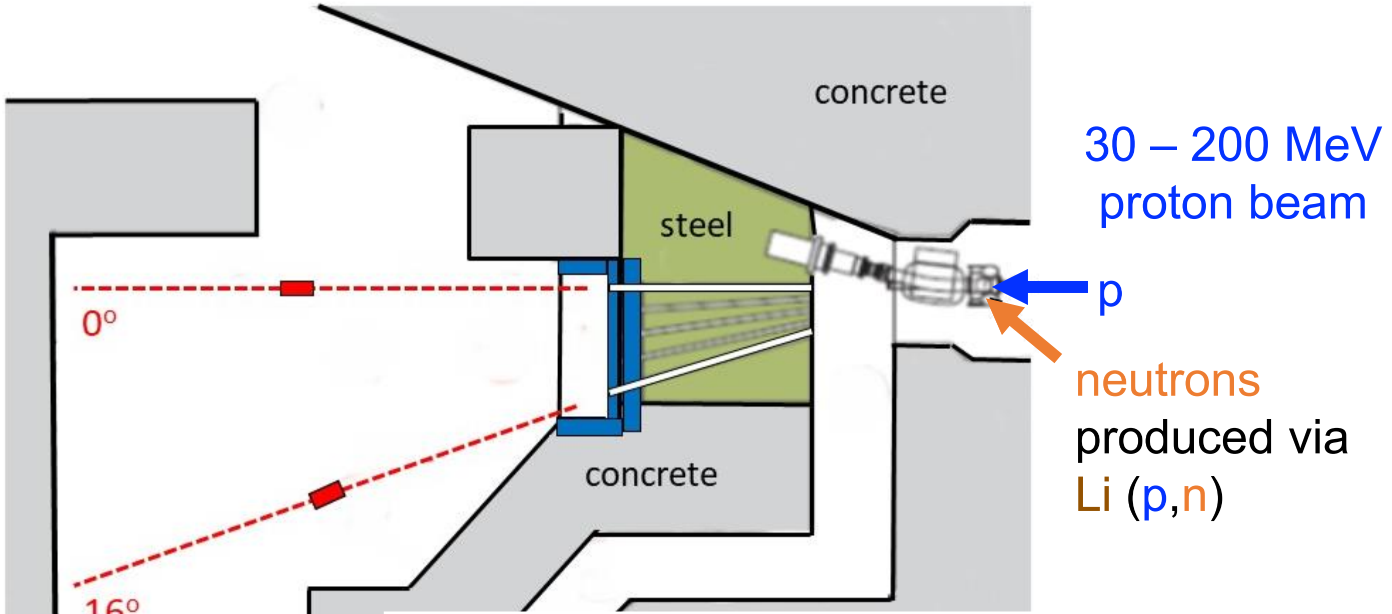
Fast neutron beam facility at iThemba LABS

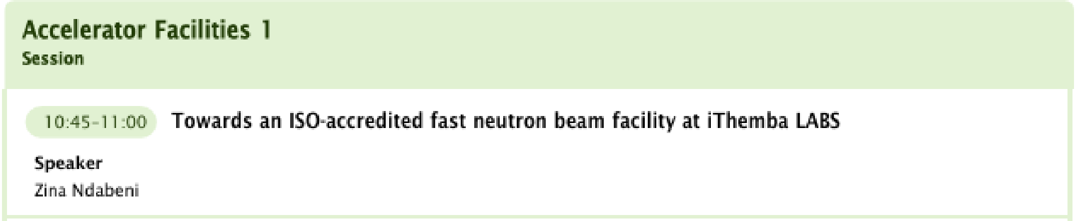


- *k* = 200 separated sector cyclotron
- Pulsed beam and long flight path for Time-of-Flight
- Calibrated detectors for energy and fluence









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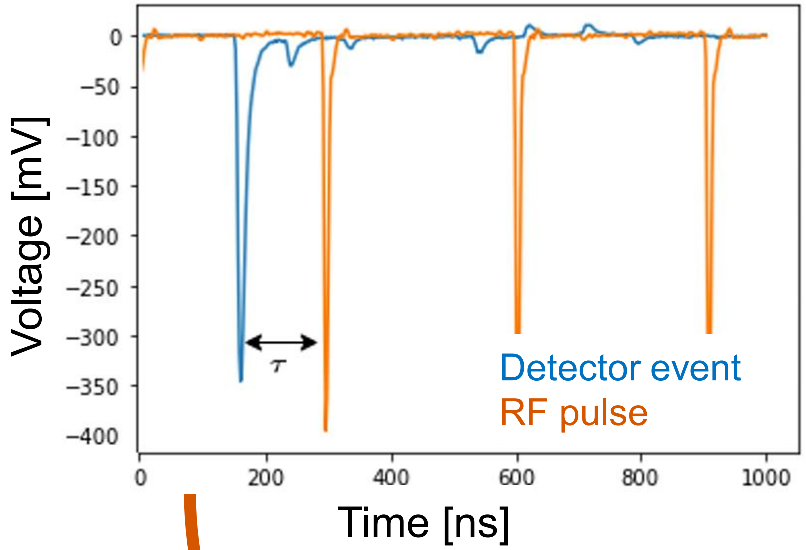
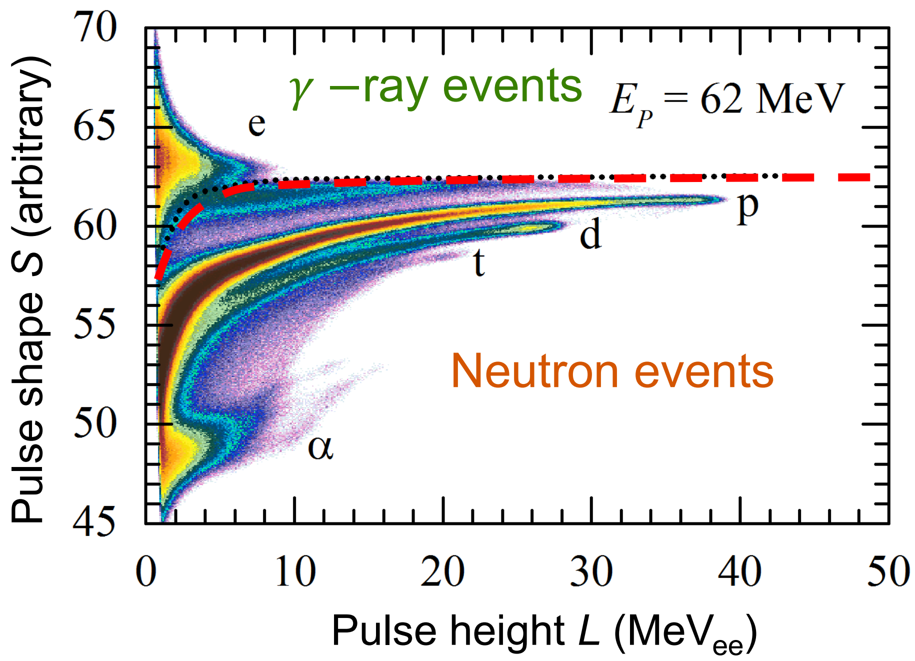
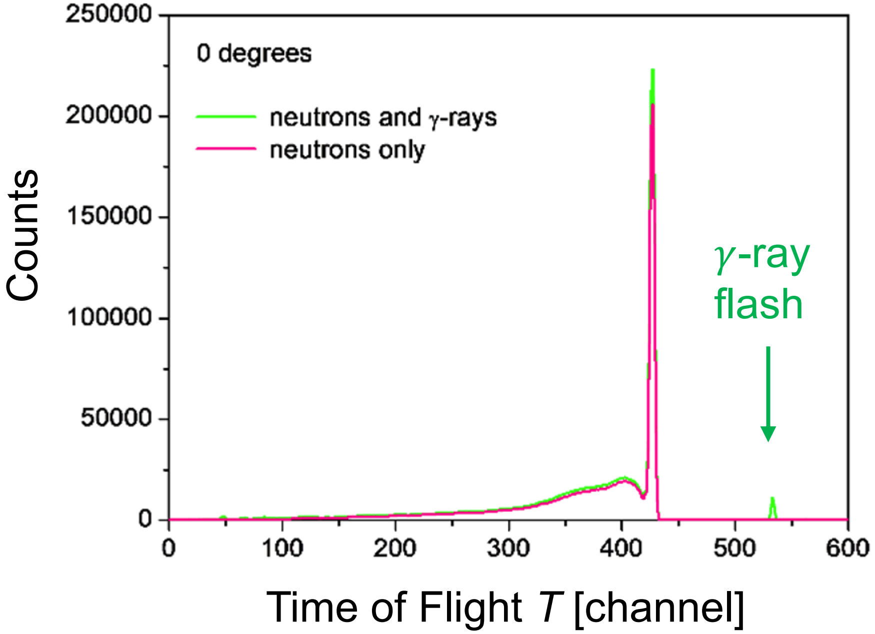
Time-of-Flight measurements

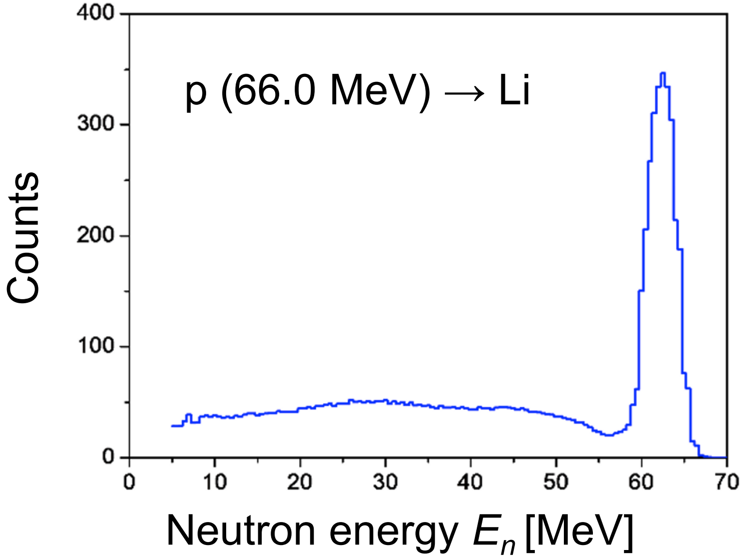


$$E_n = m_n \left(\frac{1}{\sqrt{1 - \frac{d^2}{T^2 c^2}}} - 1 \right)$$

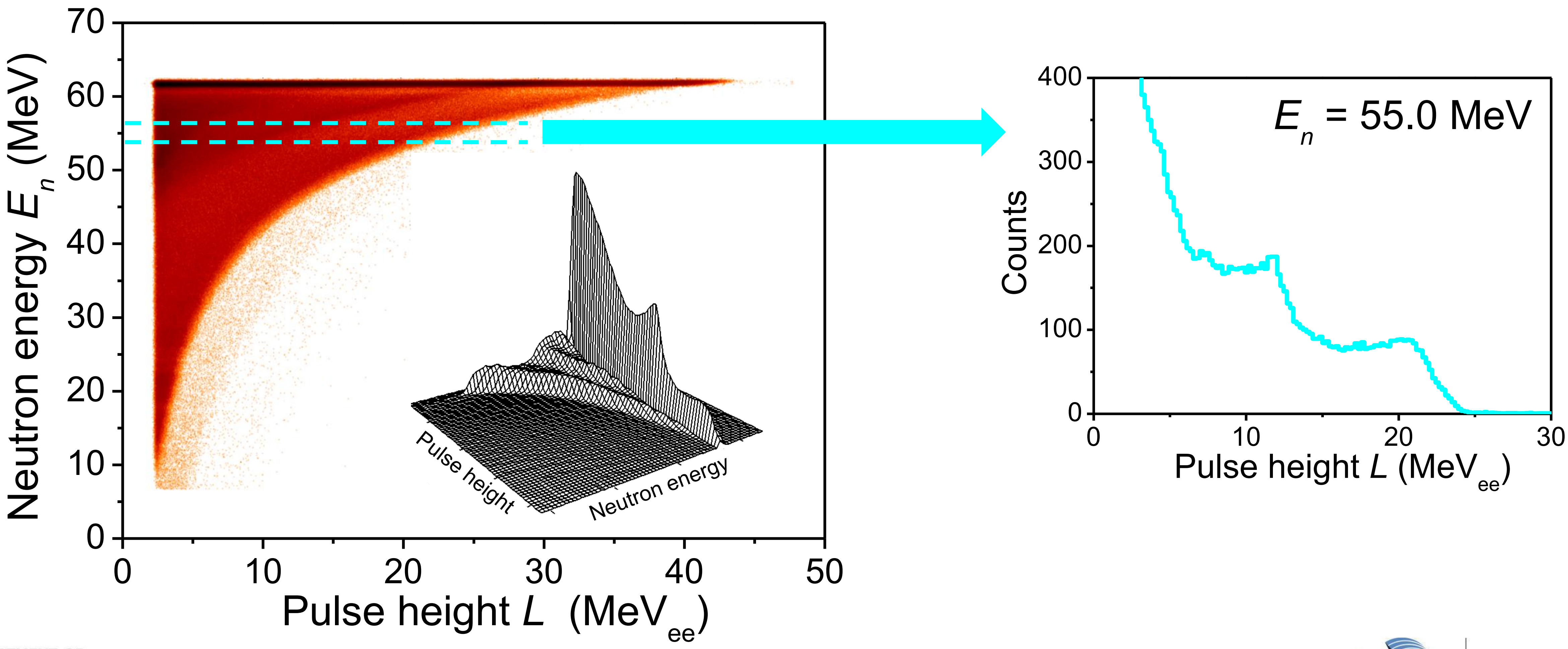
T : time-of-flight
d : target – detector distance
m_n: neutron mass







Measurements of neutron energy spectrum (via Time-of-Flight) produced by a 66 MeV proton beam irradiating a 6.0 mm Li target. with 2” x 4” BC-501A detector at 8.00 m from the target at 0°



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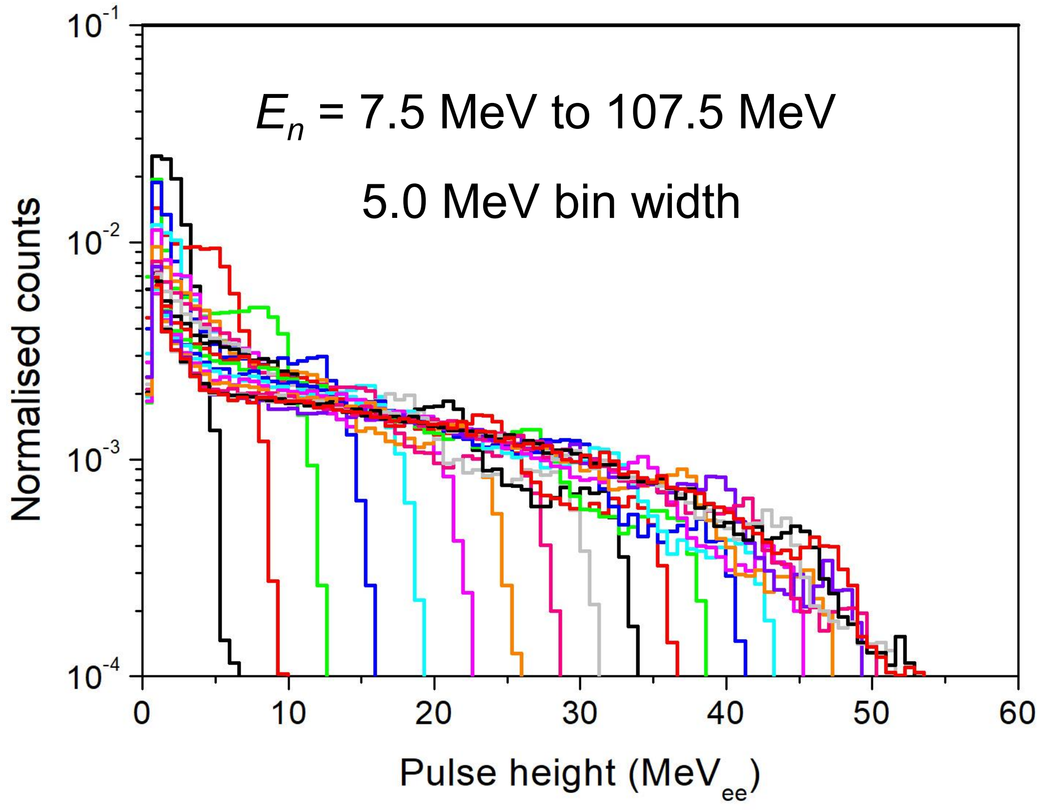
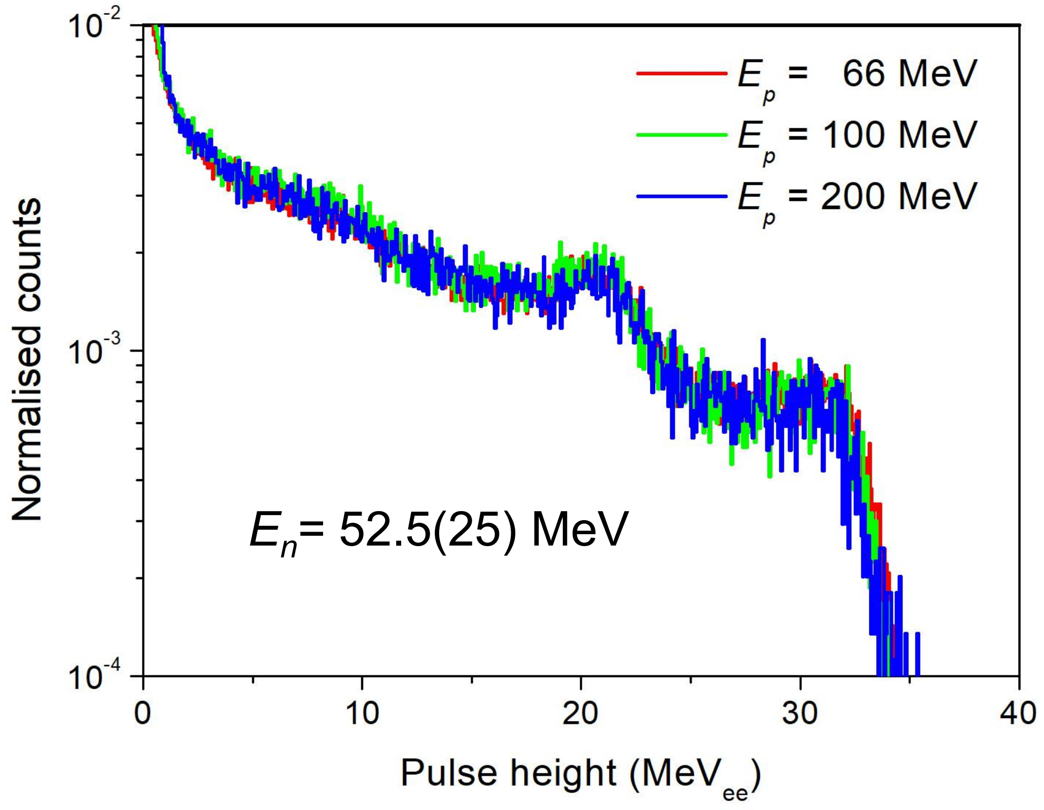
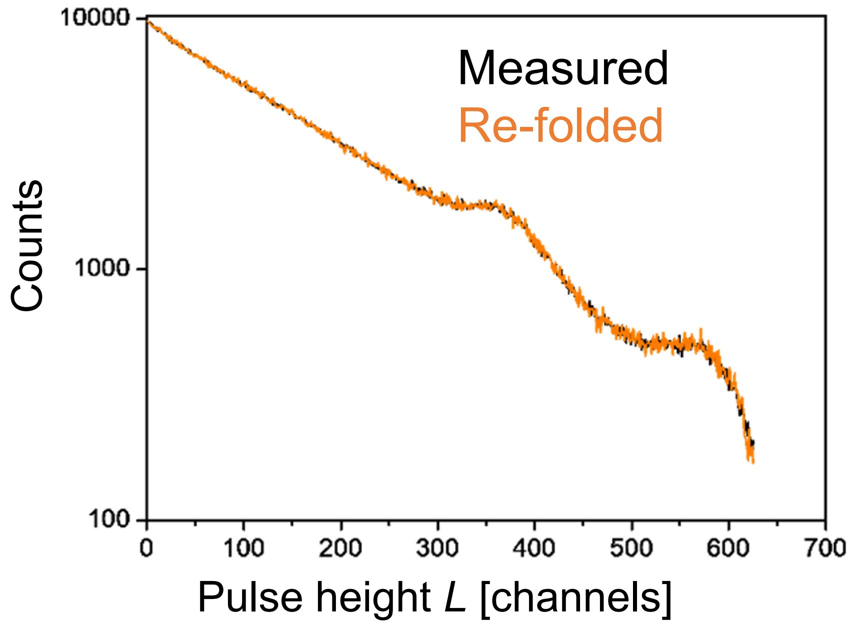
BC-501A neutron response functions using 66 MeV, 100 MeV and 200 MeV proton beams irradiating a 6.0 mm Li target

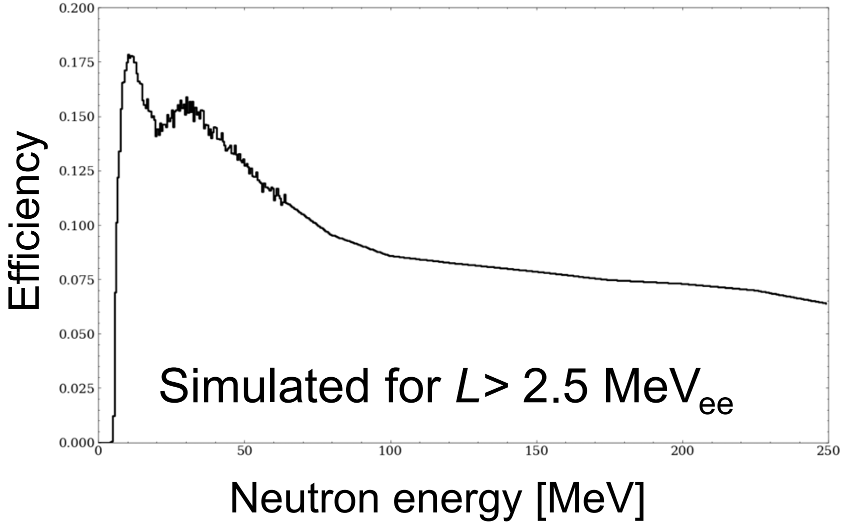




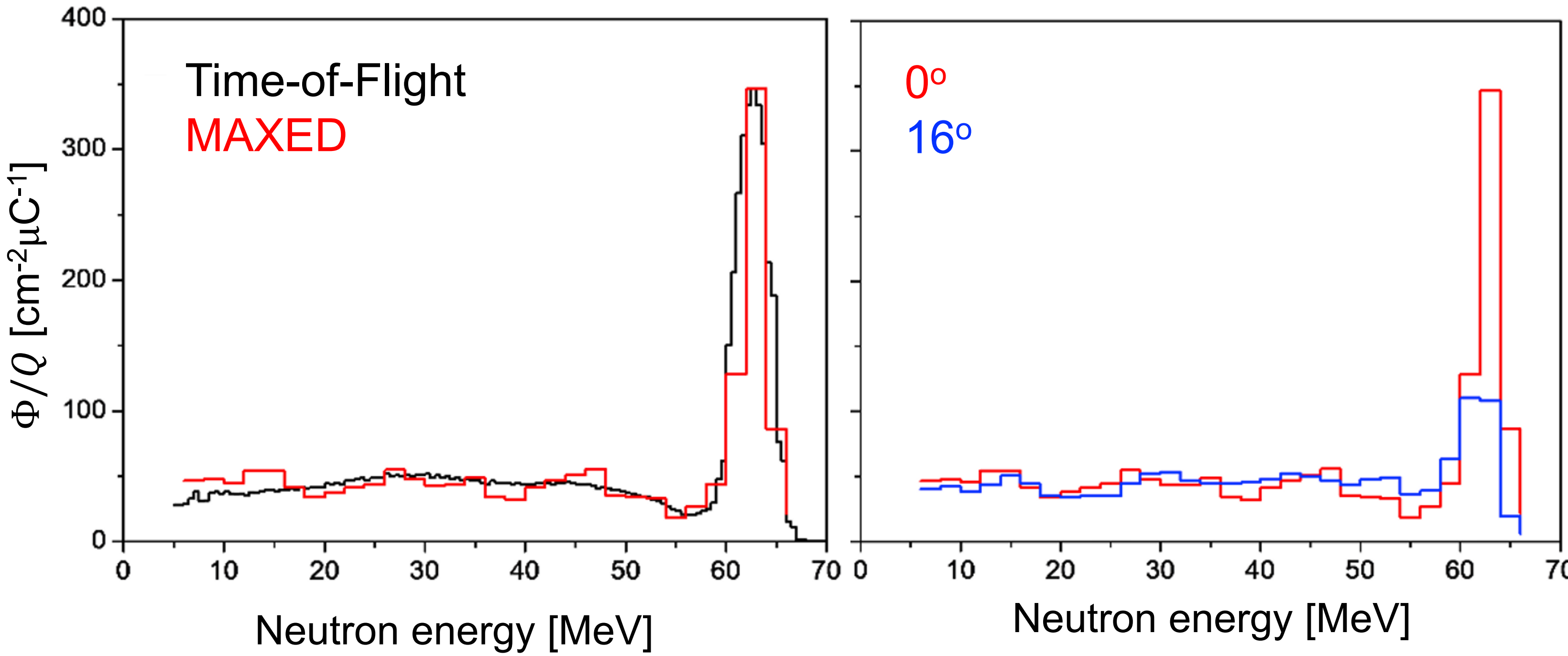
Response functions normalised to unit area

Unfolded neutron spectra for neutrons produced by 66 MeV protons on 6.0 mm Li target using MAXED.





2” x 4” BC-501A detector at 8.0 m from target



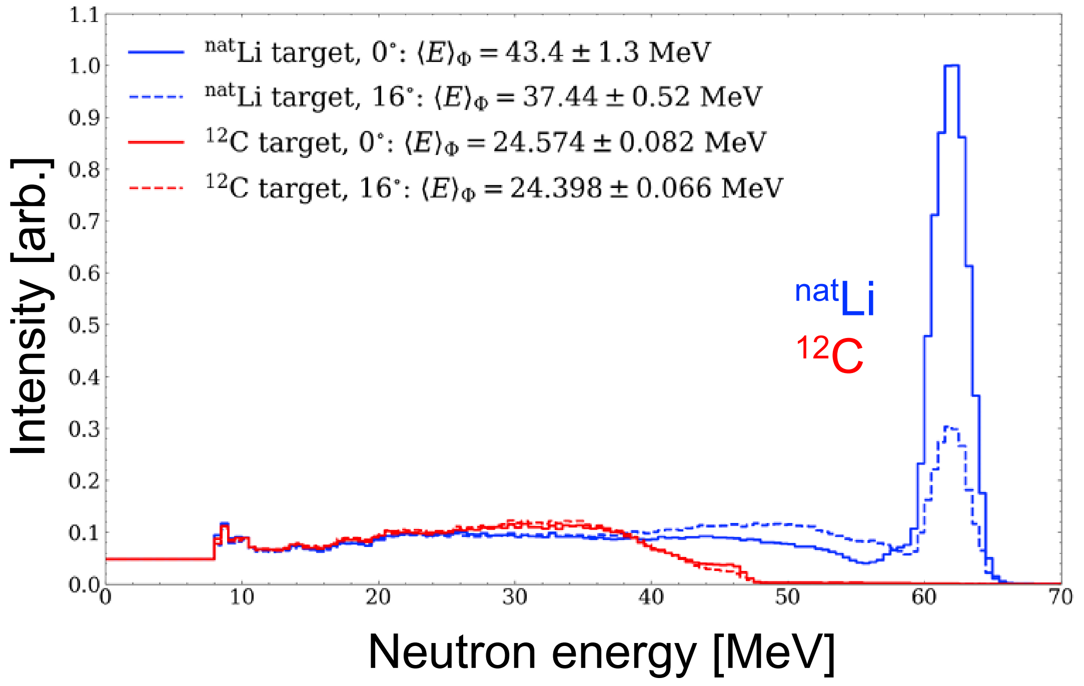
Maibane, et al. 2023

Neutron energy spectra corrected for detector efficiency (simulated) to obtain fluence.

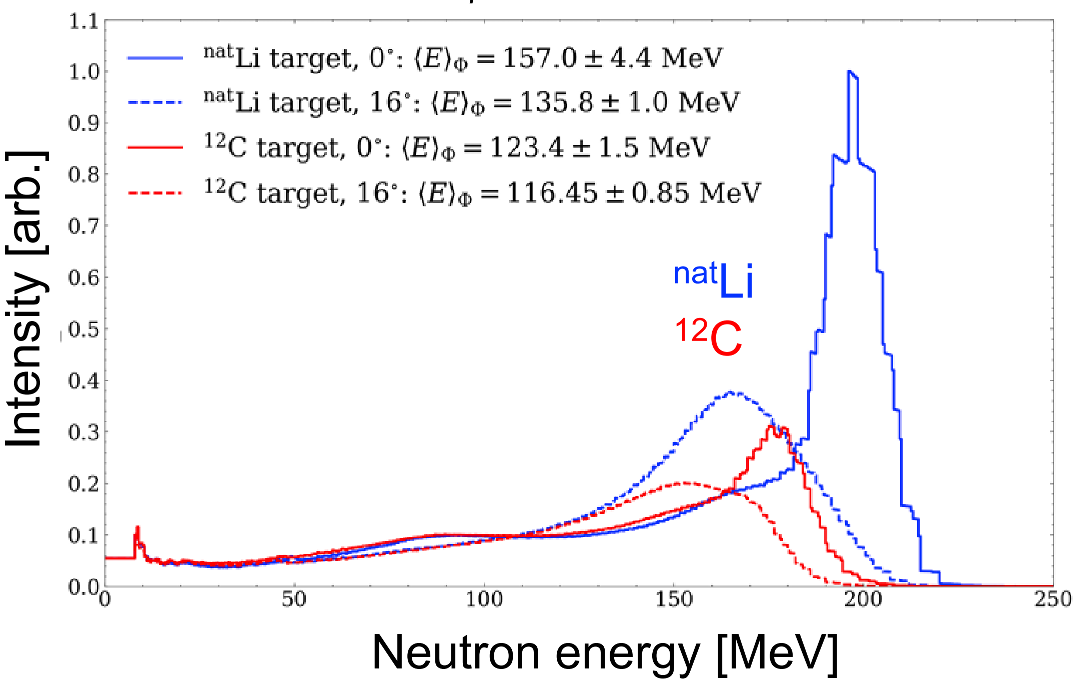
Neutron energy spectra at iThemba LABS

produced by beams of 66 MeV and 200 MeV protons on targets of ^{nat}Li and ^{12}C

E_p= 66 MeV



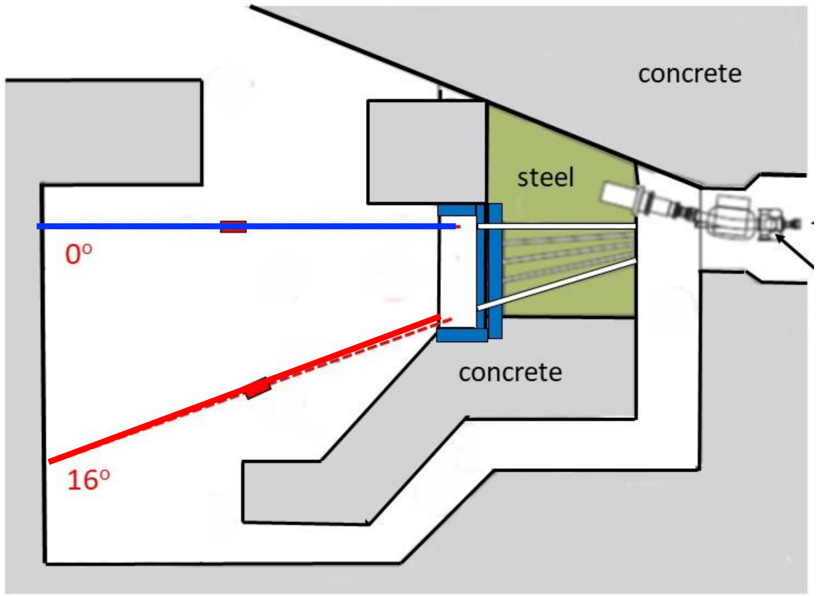
E_p= 200 MeV

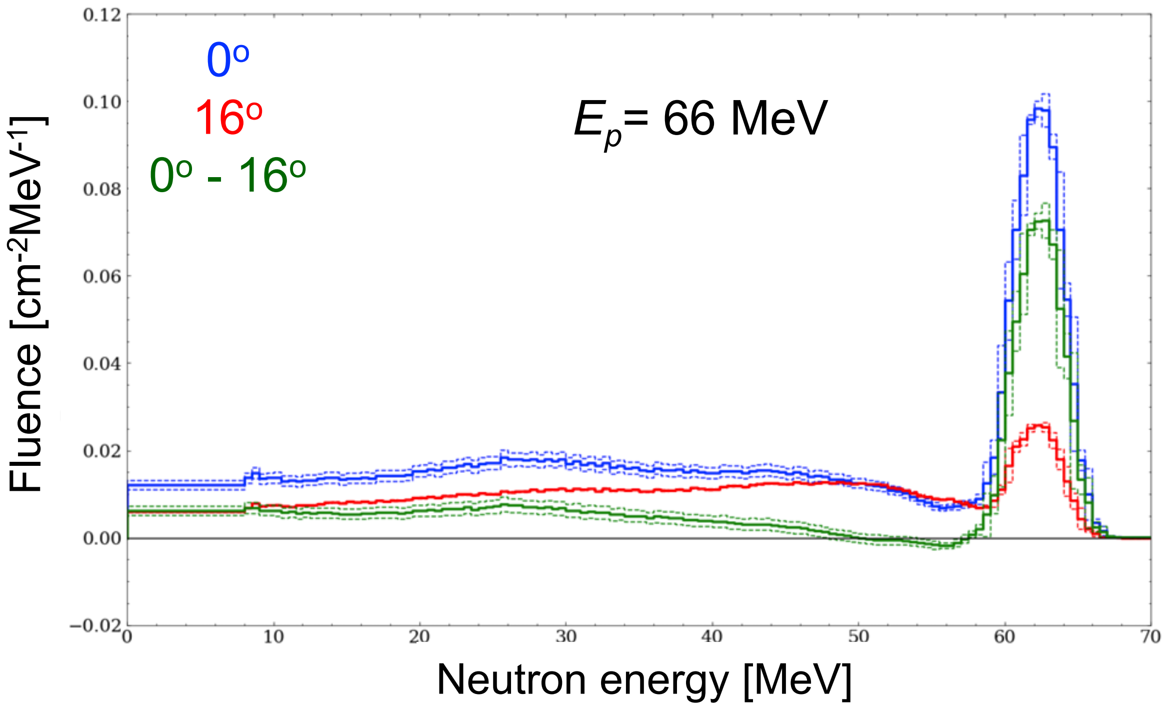


Fairall (2025) MSc Thesis, University of Cape Town.

Quasi-monoenergetic beams

Calibration of passive detectors (BSS, biological dosimetry, TEPC…) as a function of energy requires monoenergetic, or nearly monoenergetic response functions





E. Fairall (2025) MSc Thesis, University of Cape Town.

Next generation technologies

EJ-276 scintillator

previously EJ-299-33

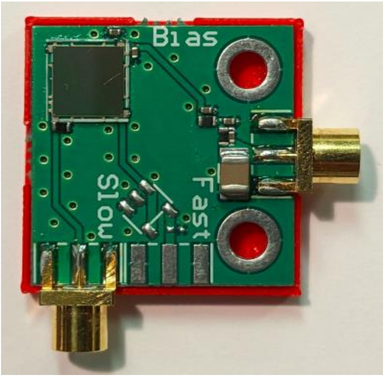
Solid (plastic)
Pulse-shape discrimination

	EJ-276 plastic	EJ-301 liquid
Light output (% anthracene)	56	78
Photons/1 MeV_{e-}	8600	12000
H:C	1.06	1.21

ELJEN TECHNOLOGY

MicroFC-60035 silicon photomultiplier

18980 microcells
Low dark current
Operating voltage: +28.5 V
Area: 6 mm x 6 mm



onsemi

DT5730 digitizer

8 channel

500 MS/s

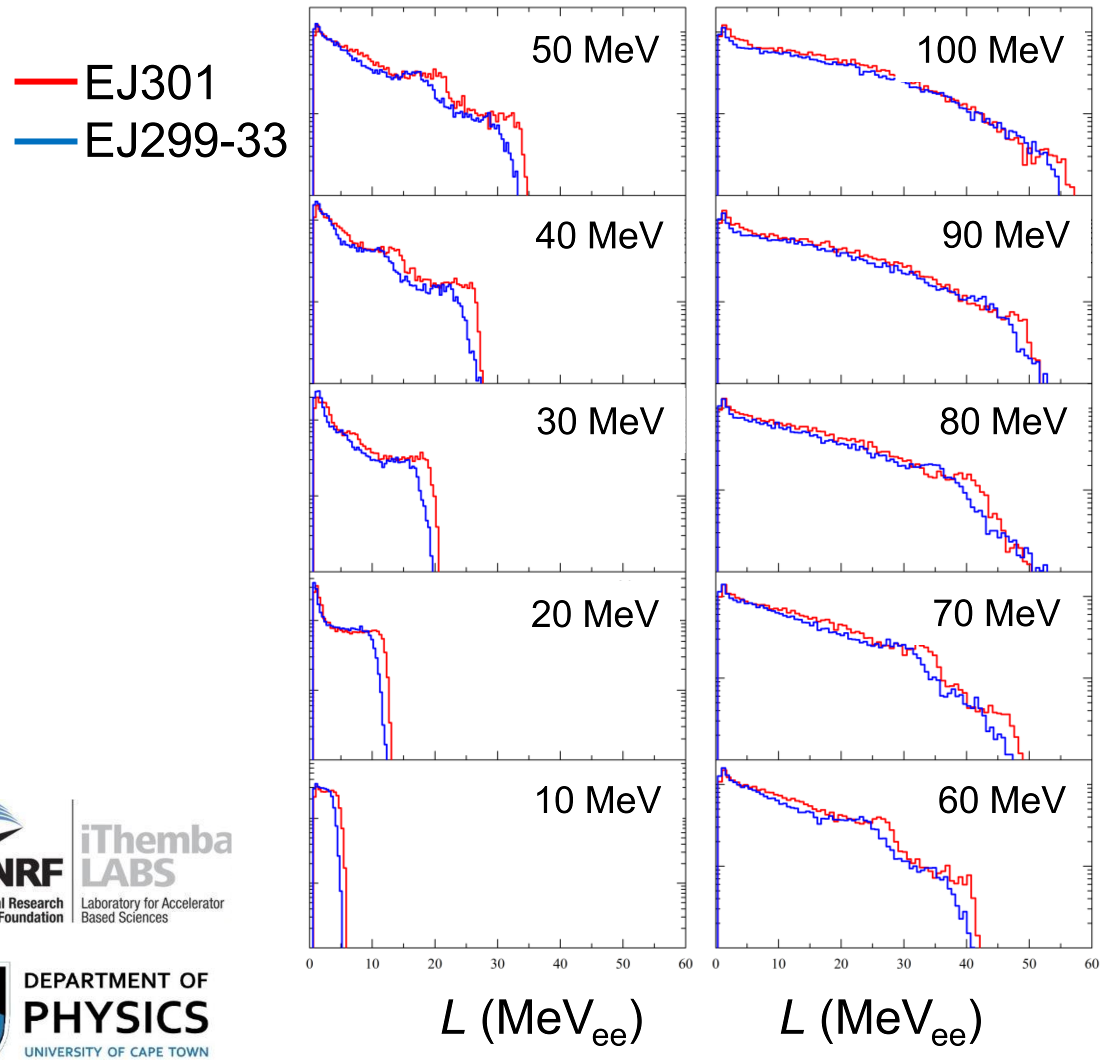
14-bit ADC 2.0 V_{pp} /0.5 V_{pp}

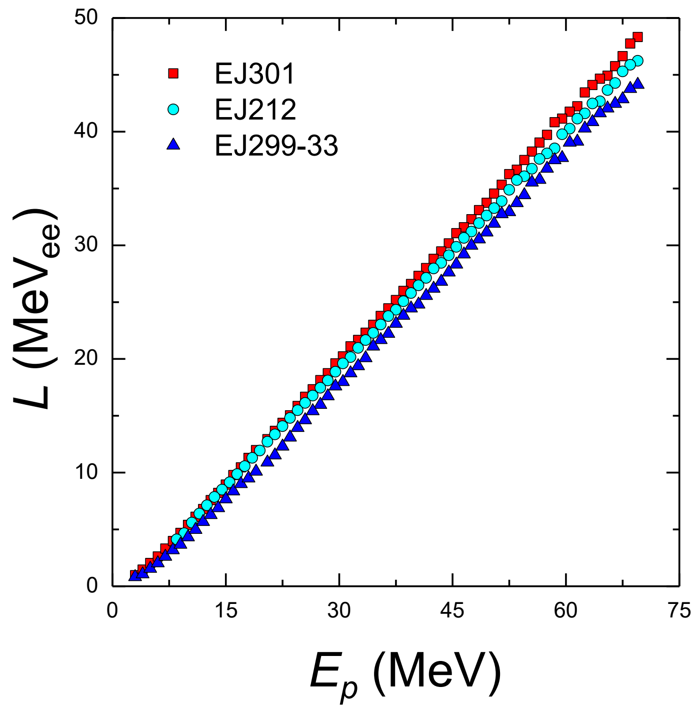
USB (30 MB/s)

Optical link (80 MB/s)

CAEN
Tools for Discovery

Measured light output spectra for neutron energies between 10 - 100 MeV, selected by Time-of-Flight for E_p= 140 MeV





1422 IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 62, NO. 3, JUNE 2015

Neutron Spectrometry with EJ299-33 Plastic Scintillator for $E_n = 10-100$ MeV

A. Buffler, A. C. Comrie, F. D. Smit, and H. J. Wörtche

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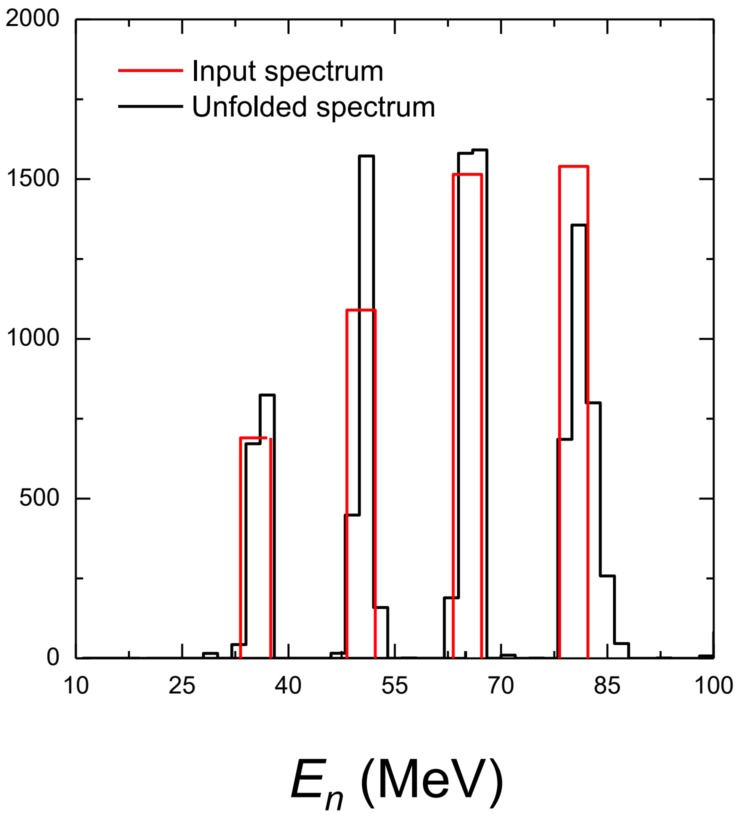
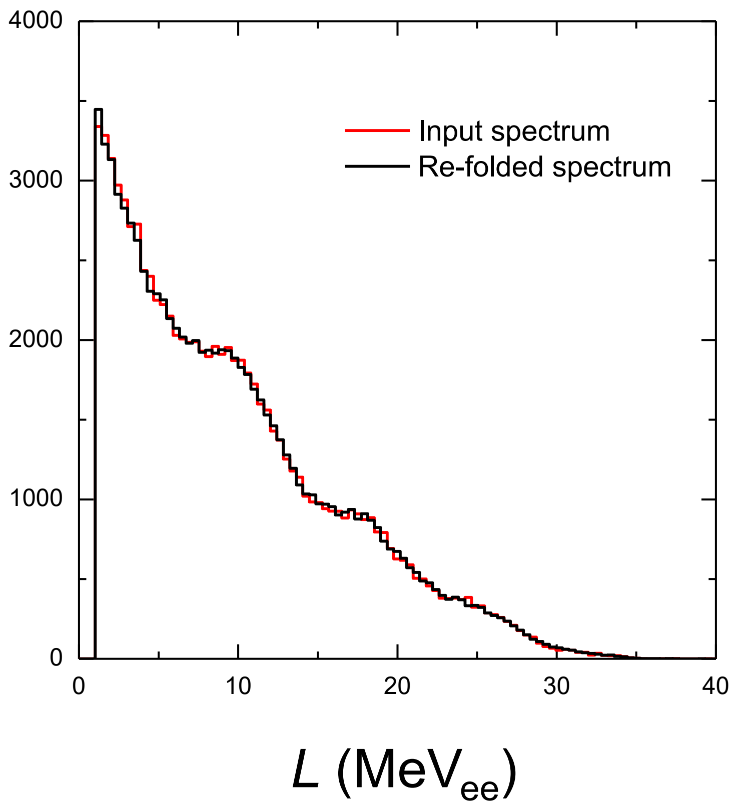
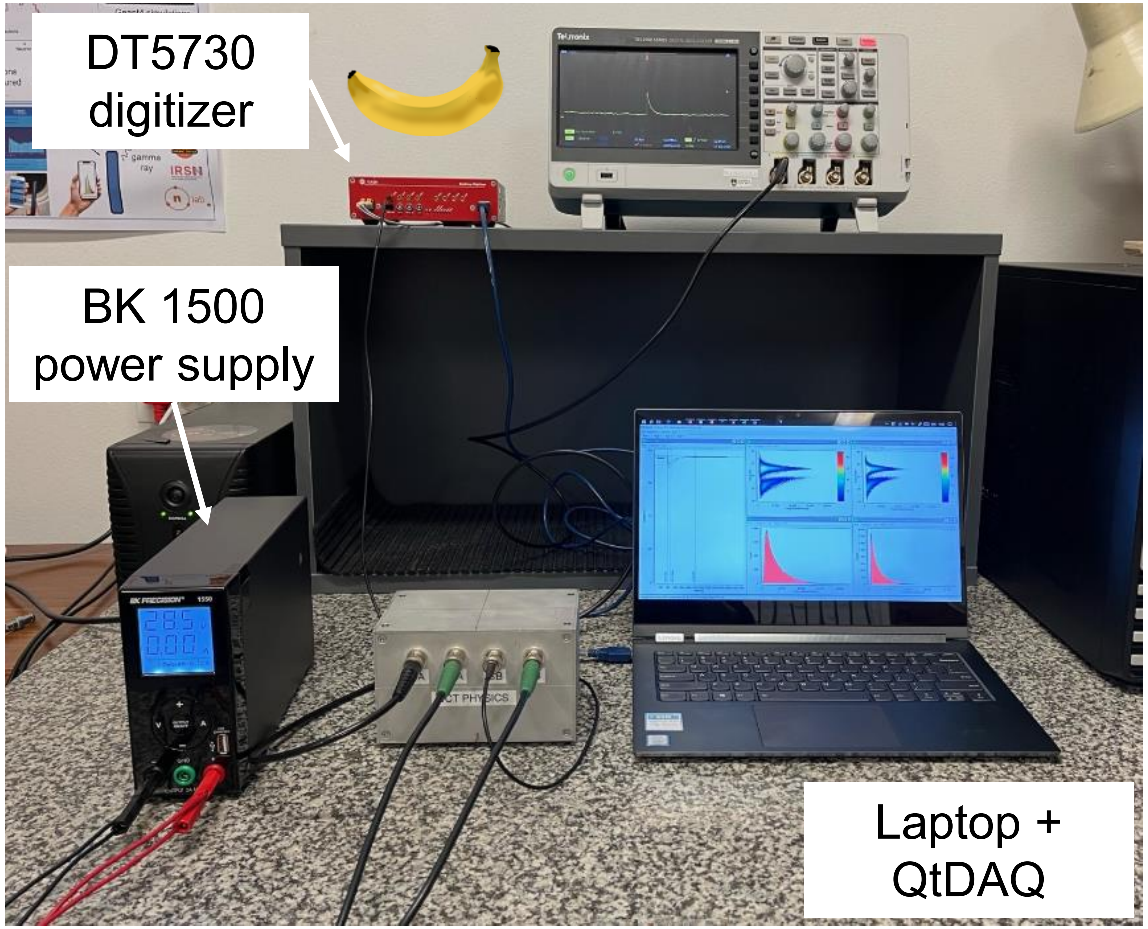
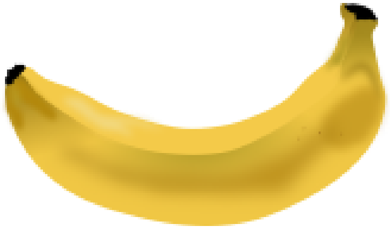
Unfolding of pulse height spectrum of "boxcar" functions with MAXED, selected by Time-of-Flight

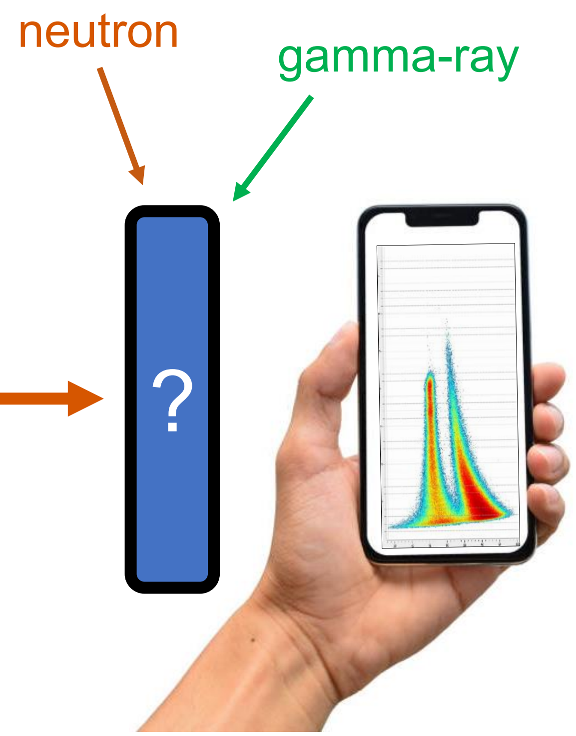




Next steps…







Measurements with 140 MeV protons at iThemba LABS in September 2025

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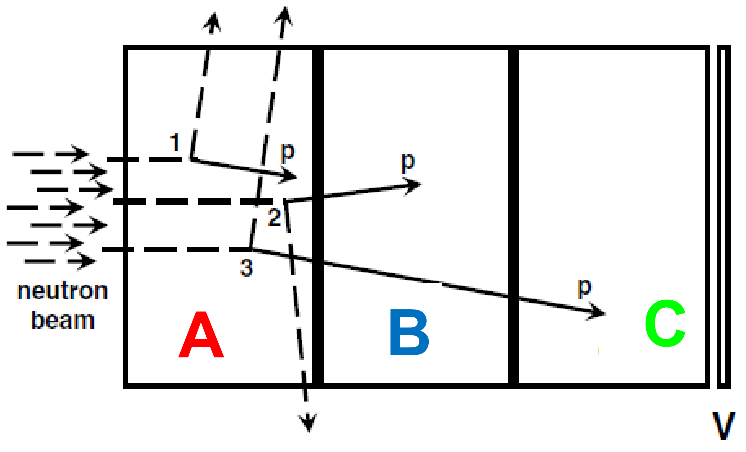
ASNR Autorité de sûreté nucléaire et de radioprotection

https://cosmic-on-air.org/

Next steps…



Radiation Protection Dosimetry (2004), Vol. 110, Nos 1-4, pp. 151–155
doi:10.1093/rpd/nch213

MEASUREMENT OF NEUTRON FLUENCE SPECTRA UP TO 150 MeV USING A STACKED SCINTILLATOR NEUTRON SPECTROMETER

F. D. Brooks[1,*], M. S. Allie[1], A. Buffler[1], V. Dangendorf[2], M. S. Herbert[1], S. A. Makupula[1], R. Nolte[2] and F. D. Smit[3]
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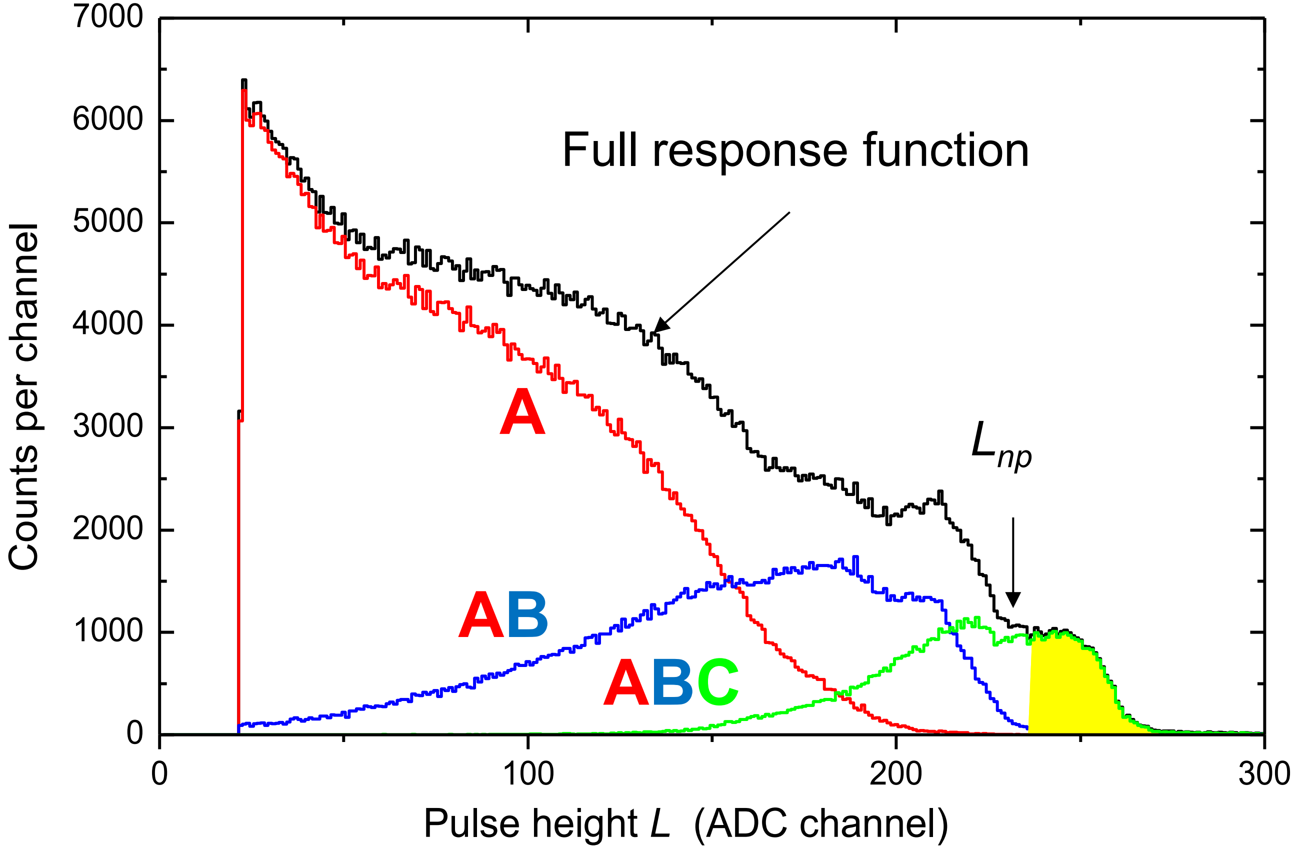
[2]Physikalisch-Technische Bundesanstalt, D-38116 Braunschweig, Germany
[3]iThemba Laboratory for Accelerator-Based Sciences, Somerset West, 7129, South Africa



Metrological and Applied Sciences University Research Unit

Summary

- Spectral measurements of neutron fields in situ require accurate and traceable detector response functions
- Below 20 MeV simulations are generally considered reliable
- Above 20 MeV only measured response functions are currently viable
- High energy neutron facilities with Time-of-Flight and quasi-monoenergetic capabilities are essential for the calibration of detectors and measurement of response functions.

Thank you!

Email: tanya.hutton@uct.ac.za