# Measurement of detector response functions for fast neutron spectroscopy with organic scintillators

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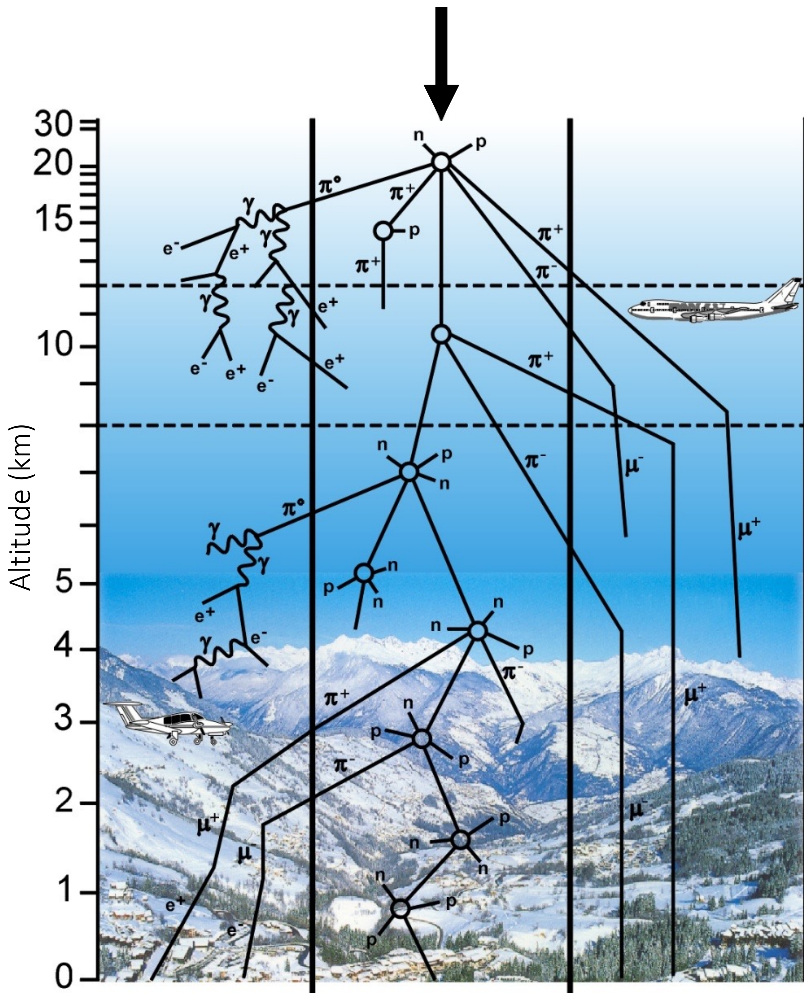
# Neutron production from cosmic rays

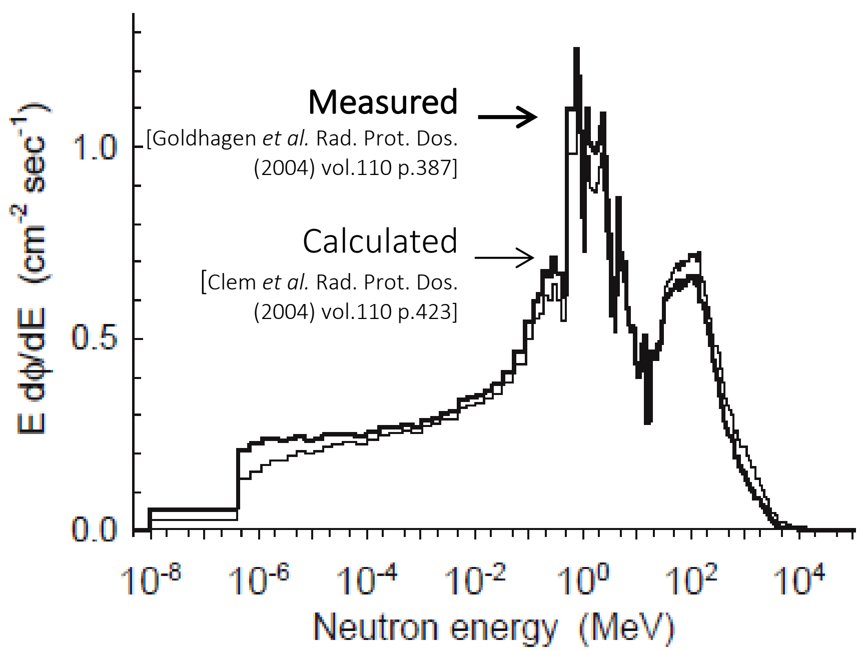



Cosmic rays:

- Galactic cosmic radiation (GCR)
- Solar energetic particles (SEP)

Neutrons are produced from evaporation of highly energetic nuclei, knock-on in peripheral collisions, or in charge exchange reactions.

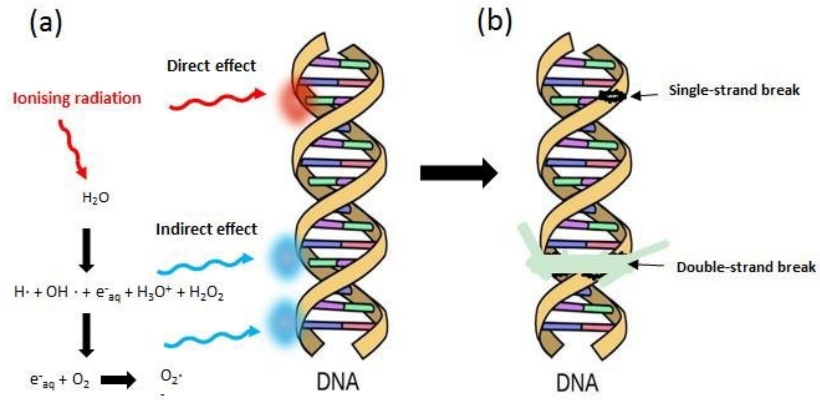
Cosmic-ray neutron spectrum:
20 km at 54° N, 117° W



# Effects of high-energy neutron radiation

In biological systems:

chemical and biological damage → increased cancer risk, fetal harm etc.

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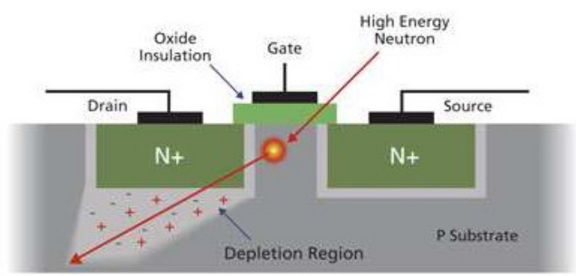


In electronic systems:

single event upsets, displacement damage, total ionizing dose → soft bit-level errors, hard errors of latch-up and burn-out etc.

Concerns for aviation, space missions, workplace exposure, radiation therapy etc.

Very little information is available on the effects of high energy neutrons due to a lack of suitable measurement devices.

# South African Space Neutron Initiative (SASNI)

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SANSA
SOUTH AFRICAN NATIONAL SPACE AGENCY

NRF
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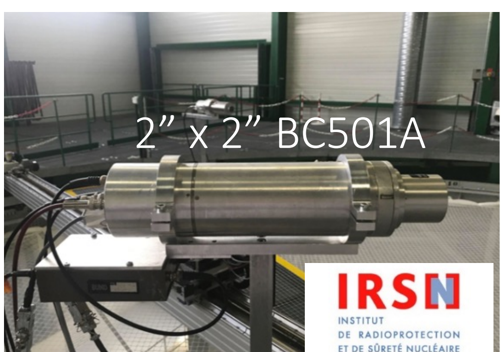
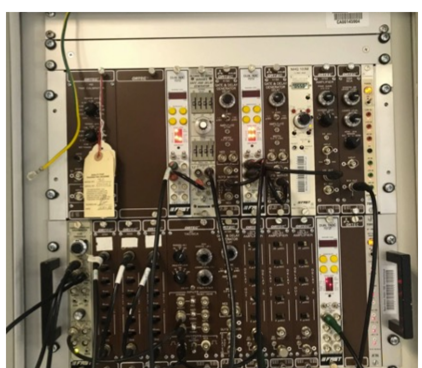
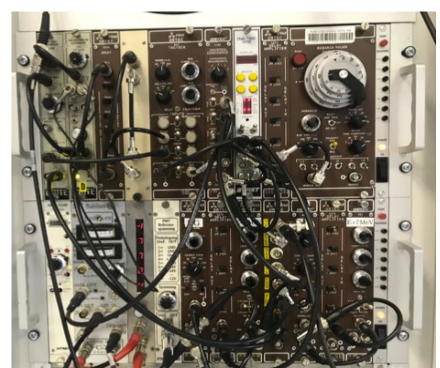
- Geographical importance
- Space weather and radiation protection policy (SANSA)
- Fast neutron reference beams (iThemba LABS)
- Instrumentation for fast neutron spectrometry
- Biological effects of fast neutrons

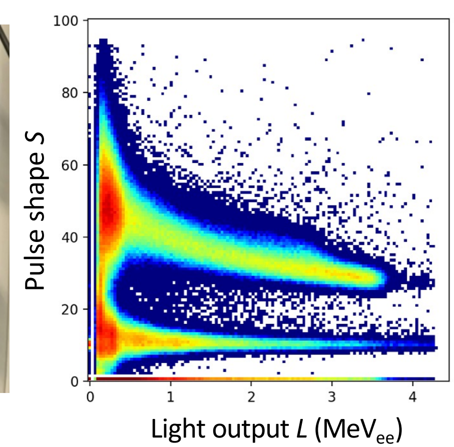
# Organic scintillators

- C, H based scintillation medium e.g. EJ-301/BC501A/NE213
- Indirect detection via $^{1}H(n, n)$ and $^{12}C(n, X)$
- Excellent energy resolution
- Fast time response
- Sensitive to all radiation types, and capable of discrimination
- Typical measurements systems are limited to use in controlled laboratory environment







# Concept for new neutron spectrometer

| | |
|---|---|
| Compact ("hand held") | Silicon photomultipliers |
| Flexible analyses | Digital signal processing |
| Neutron-gamma separation | Pulse shape discrimination |
| Safe to use in extreme environments | Plastic organic scintillators |
| Neutron spectrometer over wide energy range (1-100 MeV) | Measured and simulated mono-energetic response functions |
| Flexible suite of applications | Minerals exploration, smart farming, personal and workplace dosimetry, security, dosimetry in aircraft and spacecraft, … |

# Detector design

## Plastic scintillator

ELJEN TECHNOLOGY

### EJ-276

Pulse shape discrimination
Light output: 56% anthracene
0.6 x 0.6 x 12 cm$^3$

## Silicon photomultiplier (SiPM)


sensL
sense light

### MicroFC-60035

Area: 6 x 6 mm$^2$
18980 microcells
Operating voltage: +28.5 V

## Digital data acquisition


CAEN
Tools for Discovery

### DT5730

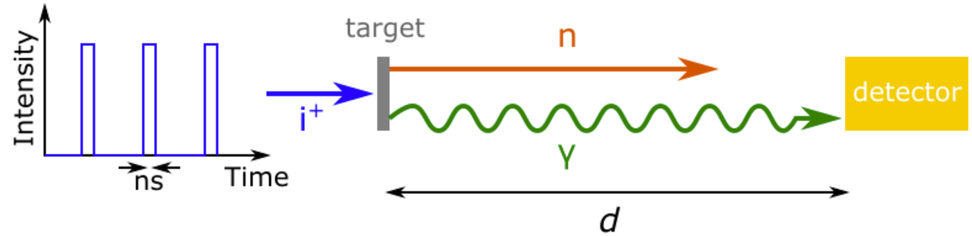
14 bit, 0.5 GS/s
0.5-2.0 $V_{pp}$
QtDAQ acquisition software

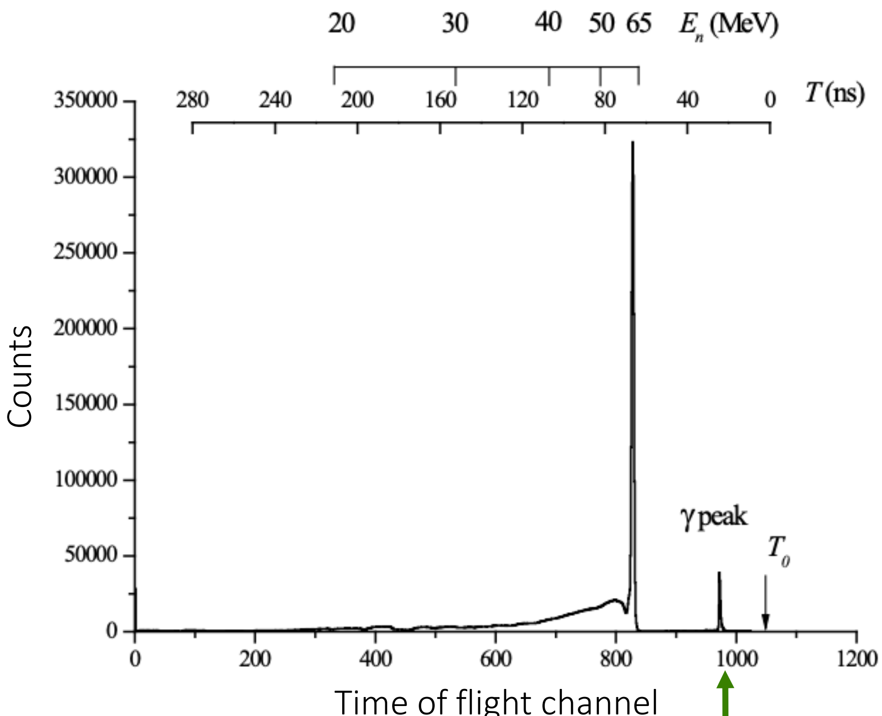

https://github.com/veggiesaurus/qtdaq

# Neutron spectroscopy: time-of-flight

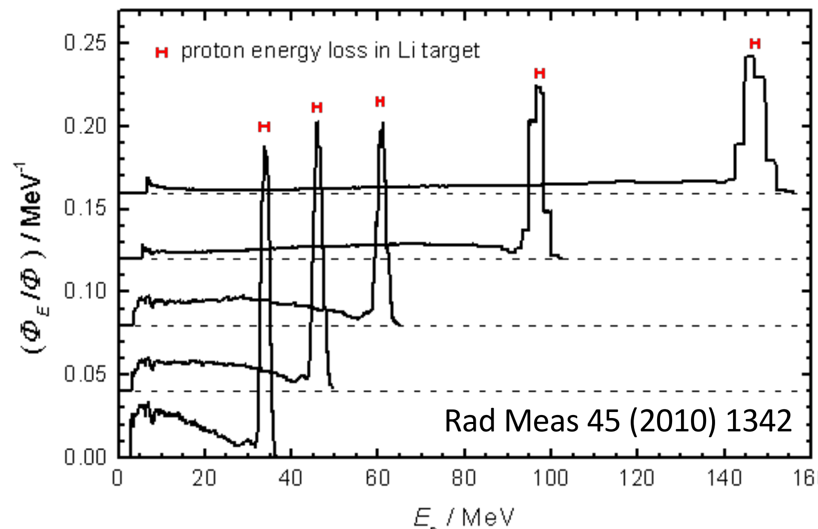
Time of arrival used to determine neutron energy.

Requires ns-pulsed neutron beam, and a sufficiently long flight path (*d*).



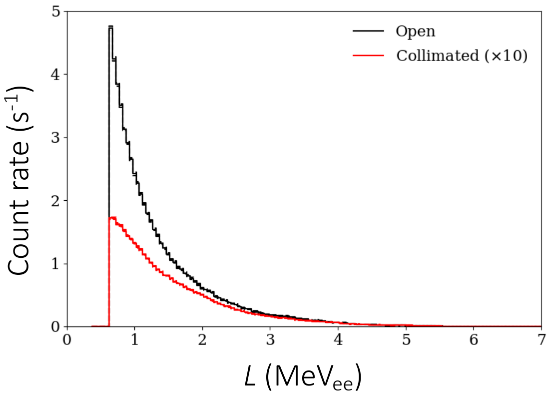




$$T = t_n - t_\gamma + d/c$$

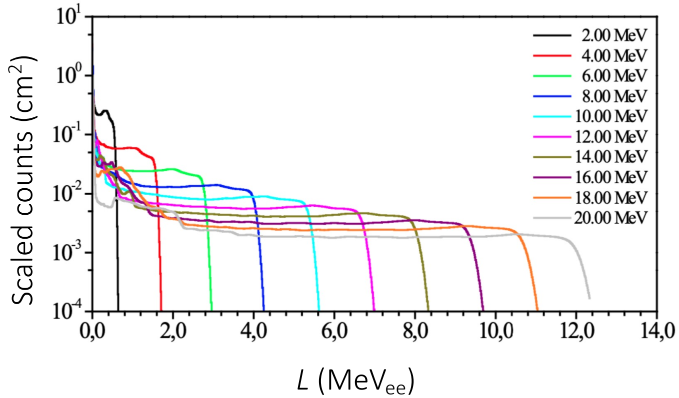



$$E_n = mc^2\left[\frac{1}{\sqrt{1-(d/cT)^2}} - 1\right]$$

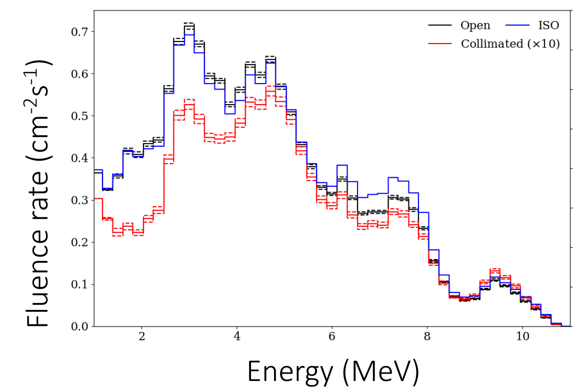
# Neutron spectroscopy: unfolding




Measured neutron pulse height spectrum …




… is **unfolded** using a known detector response matrix …




… to produce the neutron energy spectrum

UMG-3.3 unfolding package (GRAVEL & MAXED)

- Allows for spectroscopy outside the laboratory
- Requires accurate response functions
  … either simulated (< 20 MeV) or measured (>20 MeV)

# Fast neutron reactions on ${}^{12}$C

## 14 MeV

${}^{12}\mathrm{C}\,(n, n){}^{12}\mathrm{C}$
${}^{12}\mathrm{C}\,(n, n'){}^{12}\mathrm{C}$

${}^{12}\mathrm{C}\,(n, p){}^{12}\mathrm{B}$
${}^{12}\mathrm{C}\,(n, d){}^{11}\mathrm{B}$

${}^{12}\mathrm{C}\,(n, \alpha){}^{9}\mathrm{Be}$

## 90 MeV

production of carbon isotopes

${}^{12}\mathrm{C}\,(n;n)\,{}^{12}\mathrm{C}$
${}^{12}\mathrm{C}\,(n;3n)\,{}^{12}\mathrm{C}$
${}^{12}\mathrm{C}\,(n;2n)\,{}^{12}\mathrm{C}$

production of boron isotopes

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

production of beryllium isotopes

${}^{12}\mathrm{C}\,(n;2p,n)\,{}^{10}\mathrm{Be}$
${}^{12}\mathrm{C}\,(n;2p,4n)\,{}^{7}\mathrm{Be}$
${}^{12}\mathrm{C}\,(n;d,p,n)\,{}^{9}\mathrm{Be}$
${}^{12}\mathrm{C}\,(n;2d)\,{}^{9}\mathrm{Be}$
${}^{12}\mathrm{C}\,(n;t,p)\,{}^{9}\mathrm{Be}$
${}^{12}\mathrm{C}\,(n;t,d,n)\,{}^{7}\mathrm{Be}$
${}^{12}\mathrm{C}\,(n;\alpha,2n)\,{}^{7}\mathrm{Be}$
${}^{12}\mathrm{C}\,(n;2p,2n)\,{}^{9}\mathrm{Be}$
${}^{12}\mathrm{C}\,(n;d,p)\,{}^{10}\mathrm{Be}$
${}^{12}\mathrm{C}\,(n;d,p,3n)\,{}^{7}\mathrm{Be}$
${}^{12}\mathrm{C}\,(n;2d,2n)\,{}^{7}\mathrm{Be}$
${}^{12}\mathrm{C}\,(n;t,p,2n)\,{}^{7}\mathrm{Be}$
${}^{12}\mathrm{C}\,(n;\alpha)\,{}^{9}\mathrm{Be}$

production of $\mathrm{Be}^{*} \rightarrow 2\alpha$

${}^{12}\mathrm{C}\,(n;\alpha,n)\,2\alpha$
${}^{12}\mathrm{C}\,(n;2p,3n)\,2\alpha$
${}^{12}\mathrm{C}\,(n;p,2d,n)\,2\alpha$
${}^{12}\mathrm{C}\,(n;d,t)\,2\alpha$
${}^{12}\mathrm{C}\,(n;{}^{3}\mathrm{He},2n)\,2\alpha$
${}^{12}\mathrm{C}\,(n;p,d,2n)\,2\alpha$
${}^{12}\mathrm{C}\,(n;p,t,n)\,2\alpha$

production of lithium isotopes

${}^{12}\mathrm{C}\,(n;3p,n)\,{}^{9}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;3p,3n)\,{}^{7}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;p,{}^{3}\mathrm{He})\,{}^{9}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;p,{}^{3}\mathrm{He},2n)\,{}^{7}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;p,\alpha)\,{}^{8}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;p,\alpha,2n)\,{}^{6}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;d,{}^{3}\mathrm{He},n)\,{}^{7}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;2p,d)\,{}^{9}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;2p,d,2n)\,{}^{7}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;p,2d)\,{}^{8}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;p,2d,2n)\,{}^{6}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;d,\alpha,n)\,{}^{6}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;t,{}^{3}\mathrm{He},n)\,{}^{6}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;3d)\,{}^{7}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;p,d,t,n)\,{}^{6}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;{}^{6}\mathrm{Li},n)\,{}^{7}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;2d,t)\,{}^{6}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;3p,2n)\,{}^{8}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;3p,4n)\,{}^{6}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;p,{}^{3}\mathrm{He},n)\,{}^{8}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;p,{}^{3}\mathrm{He},3n)\,{}^{6}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;p,\alpha,n)\,{}^{7}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;d,{}^{3}\mathrm{He})\,{}^{8}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;d,{}^{3}\mathrm{He},2n)\,{}^{6}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;2p,d,n)\,{}^{8}\mathrm{Li}$
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${}^{12}\mathrm{C}\,(n;3d)\,{}^{7}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;p,d,t)\,{}^{7}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;{}^{6}\mathrm{Li})\,{}^{7}\mathrm{Li}$
${}^{12}\mathrm{C}\,(n;t,\alpha)\,{}^{6}\mathrm{Li}$

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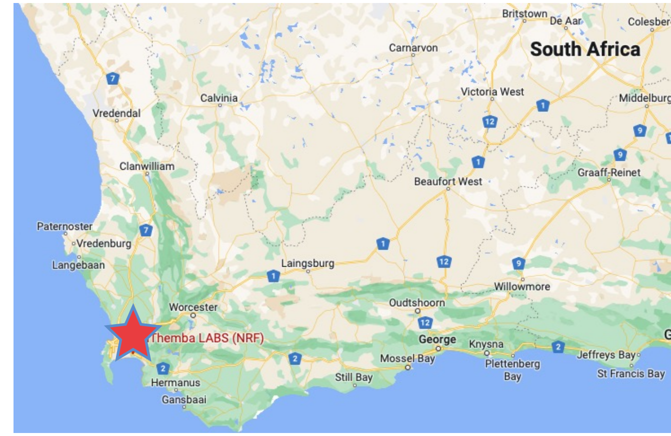
National laboratory

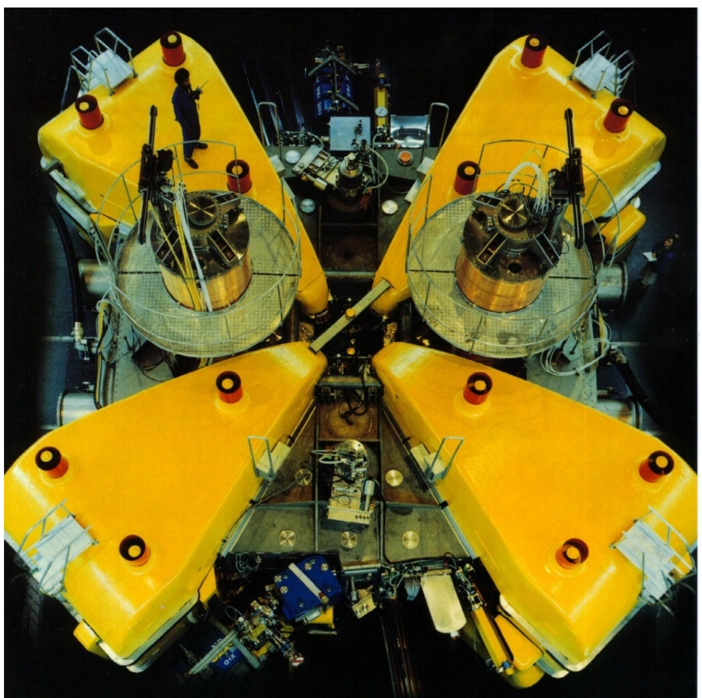
Largest accelerator in Southern Hemisphere

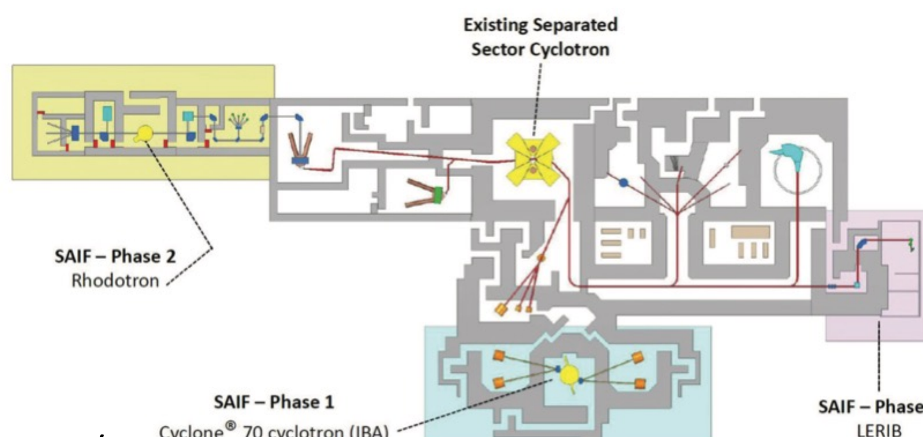
K200 Separated Sector Cyclotron

25 - 200 MeV protons

6 - 26 MHz

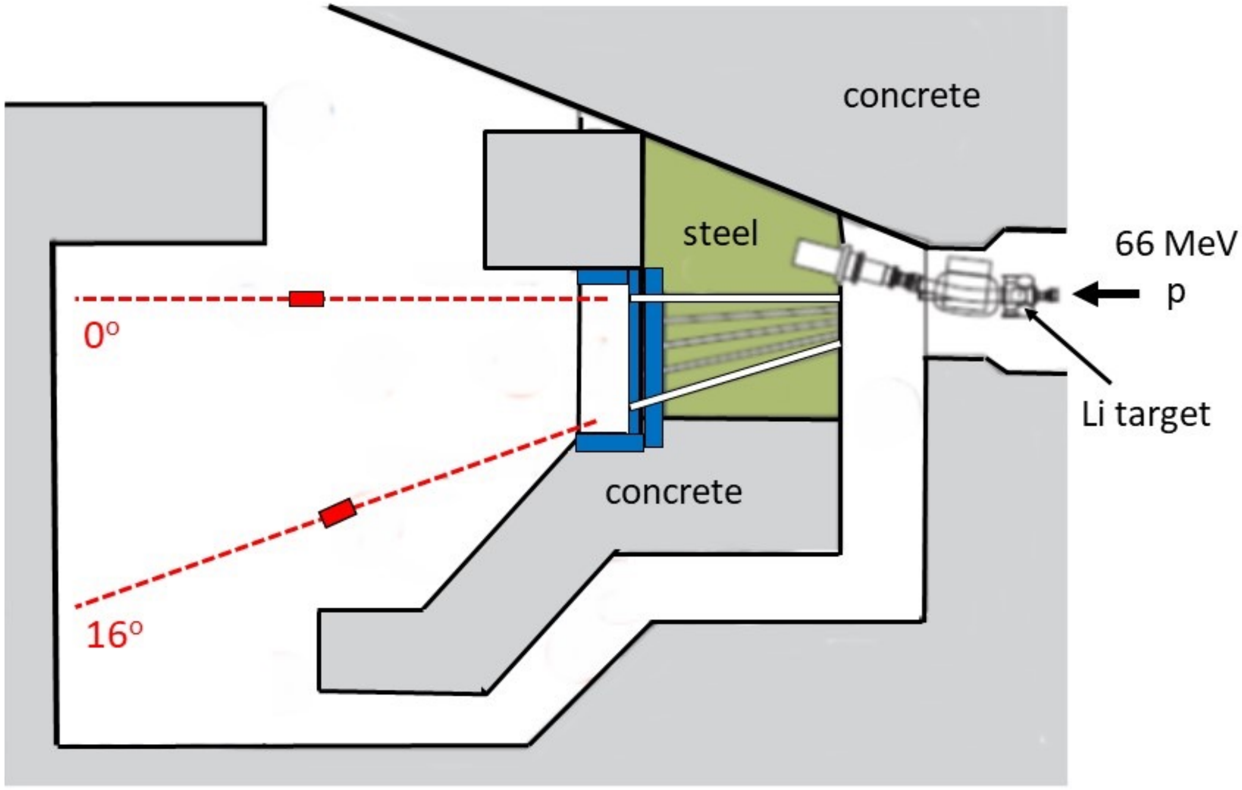


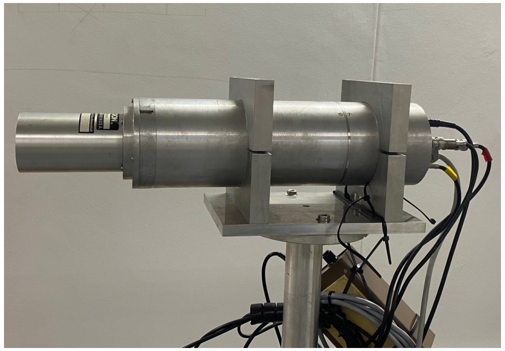



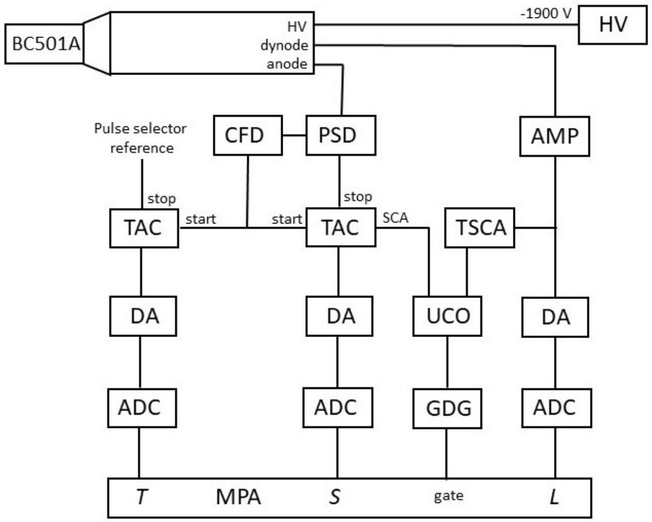



https://tlabs.ac.za/accelerators/cyclotron-parameters/

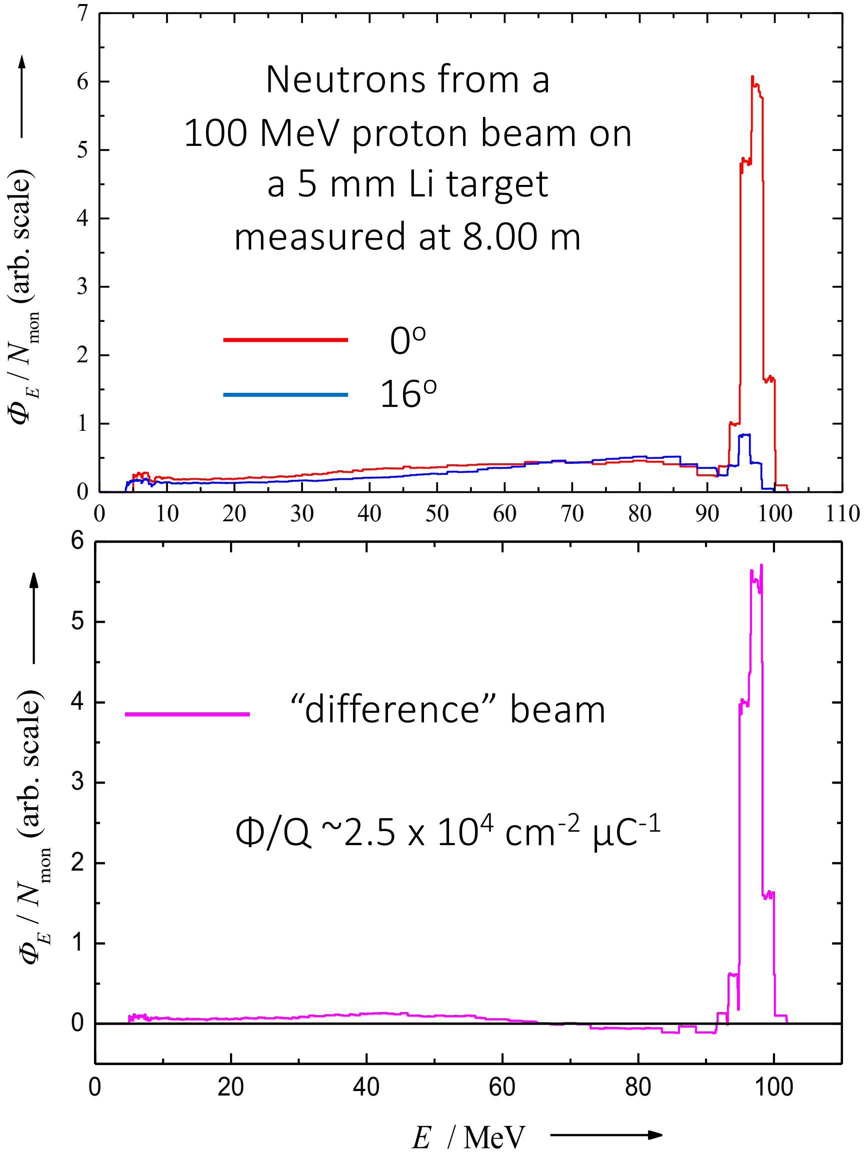
# Fast neutron beam facility at iThemba LABS



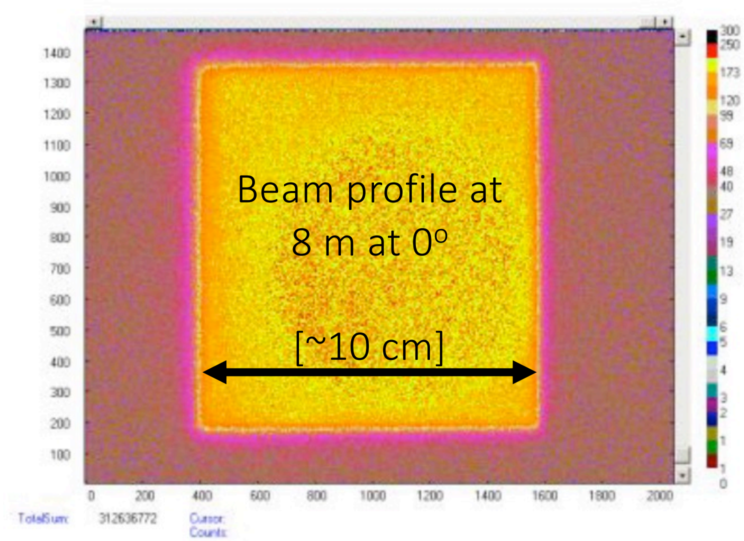


# Quasi-monoenergetic neutron beams at iThemba LABS

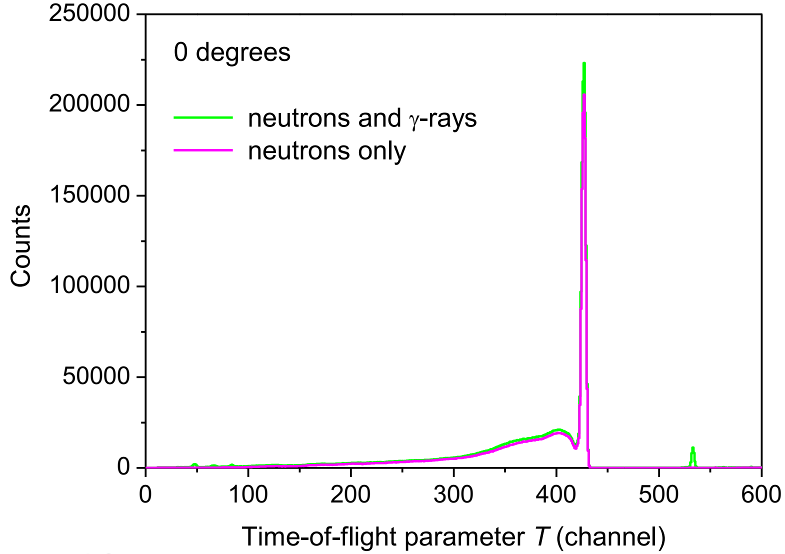


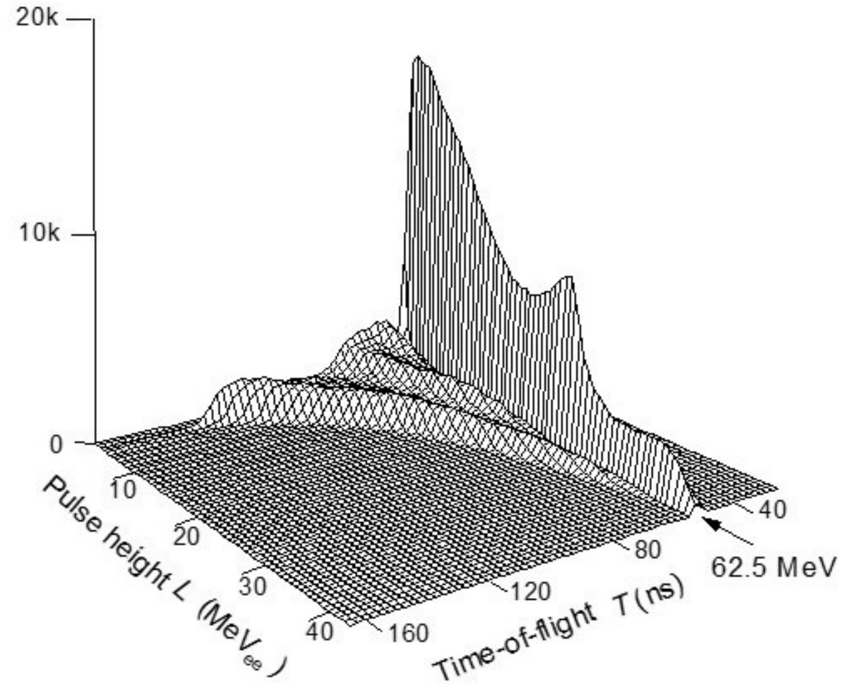

Full energy peak at ($E_p$ – Q) is strongly forward biased

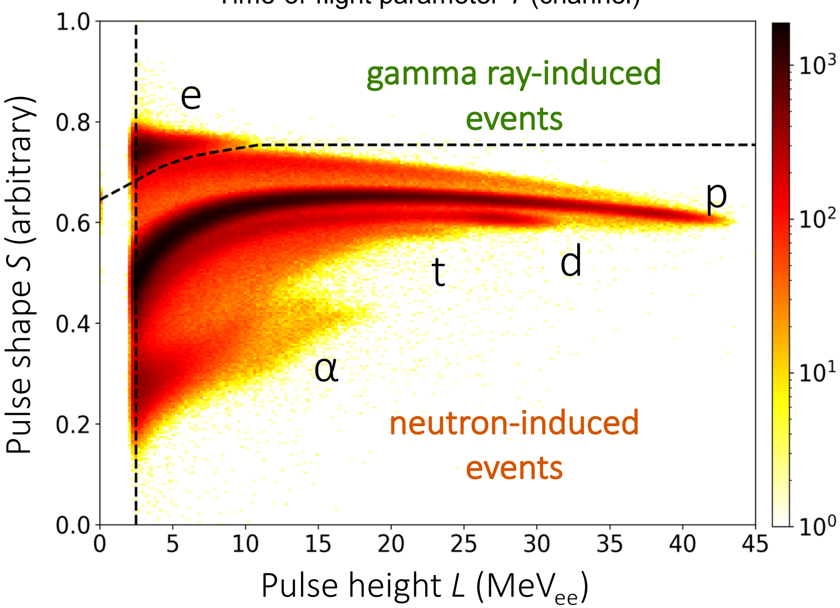
Low energy continuum from breakup reactions in target is approximately isotropic



# Time-of flight measurement of neutrons produced by a 66 MeV proton beam irradiating a 8.0 mm $^{nat}$Li target. (BC501A at 8.00 m from the target at 0°).



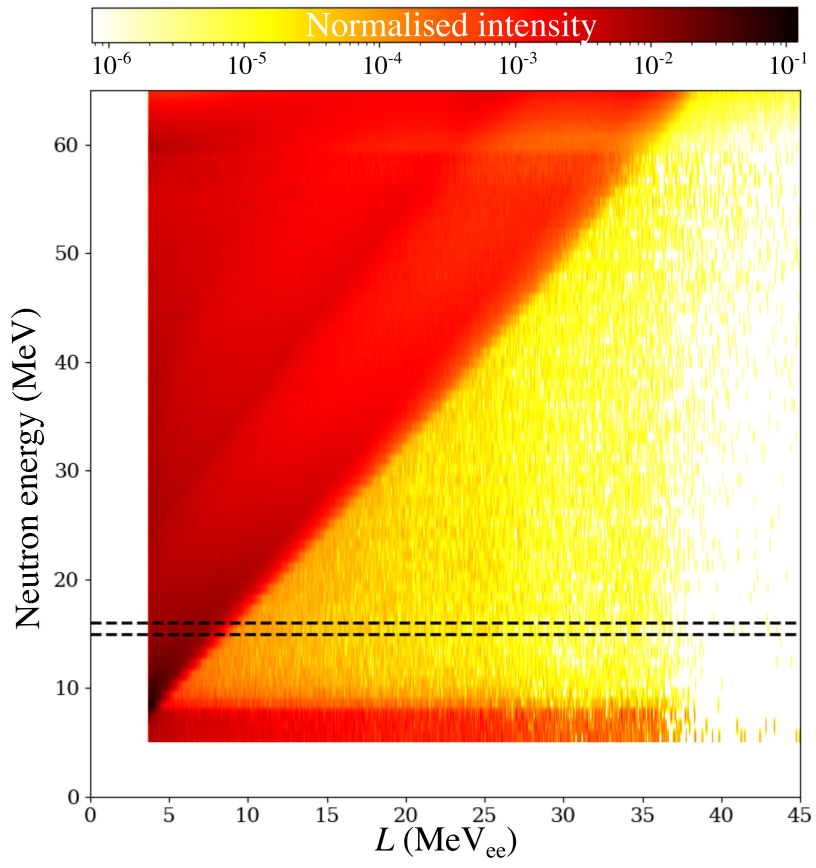



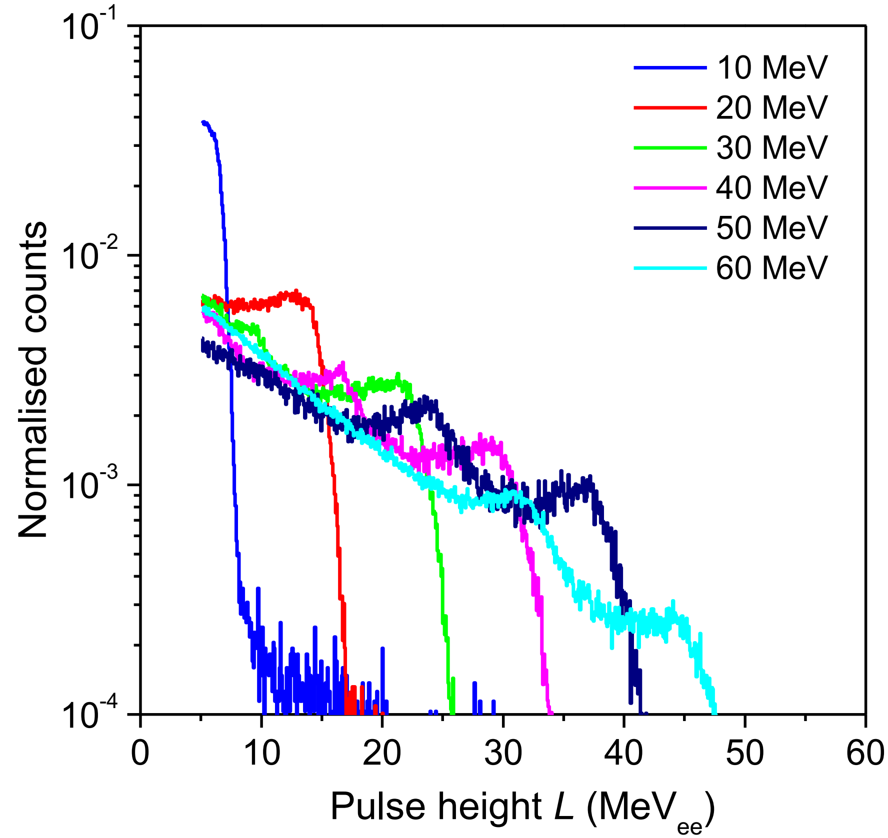




$$T = t_n - t_\gamma + d/c$$

$$E_n = mc^2 \left[ \frac{1}{\sqrt{1-(d/cT)^2}} - 1 \right]$$

# Measured light output spectra for neutron energies between 10 - 65 MeV, selected by time-of-flight for BC501A.

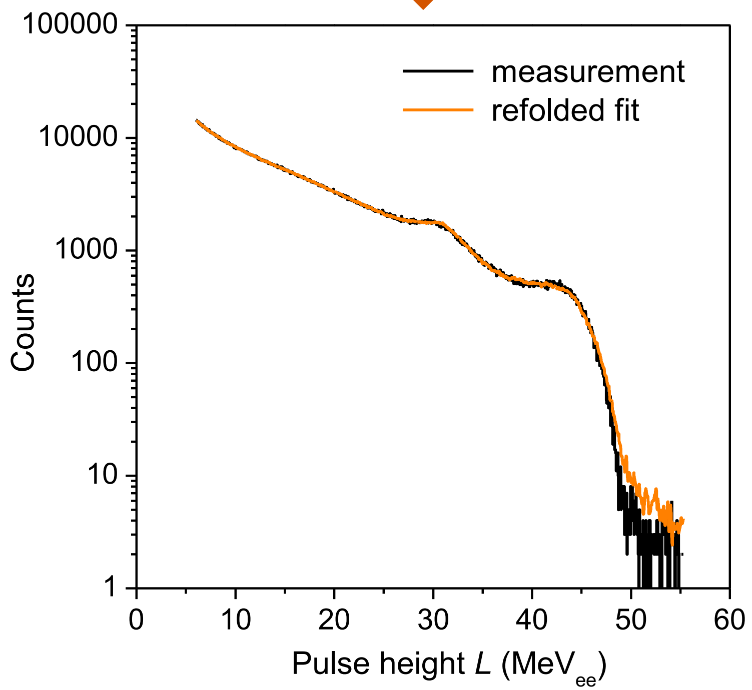


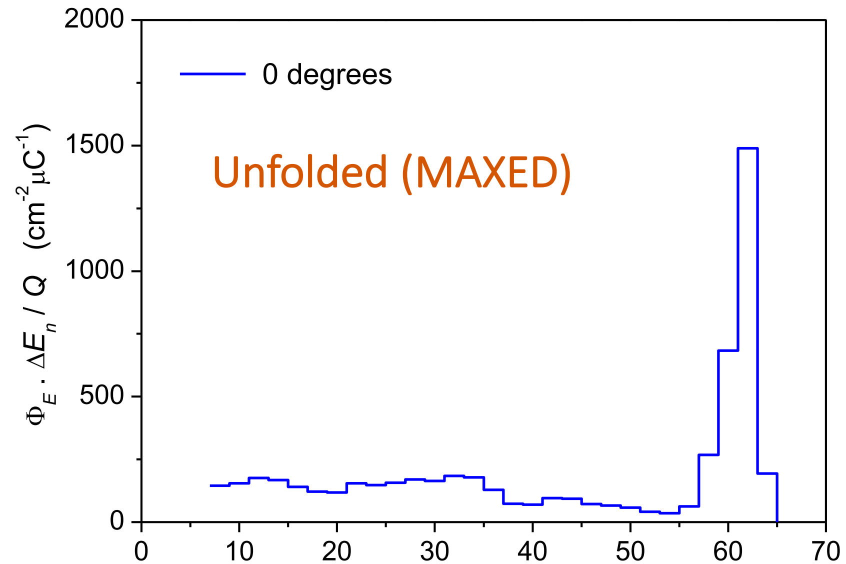



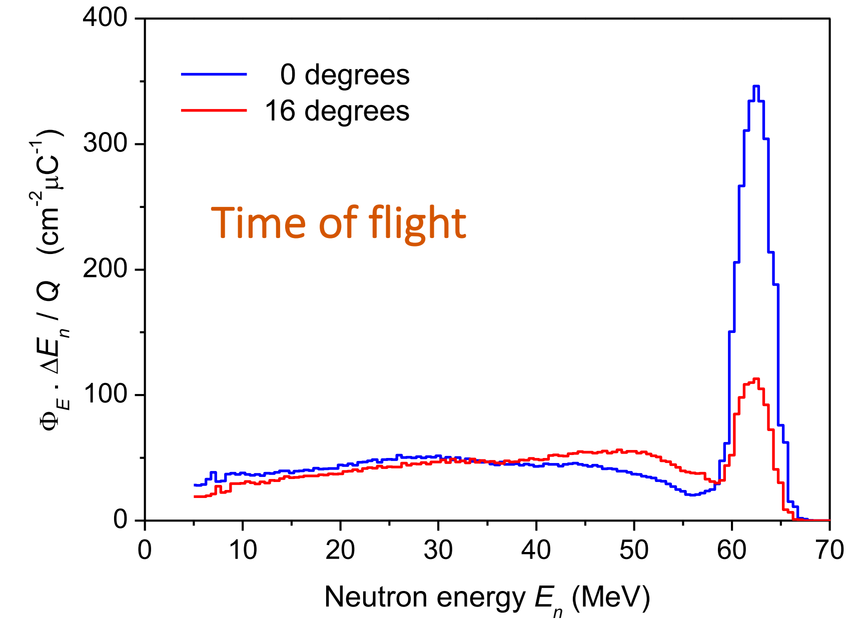
# Spectrum unfolding with measured detector response functions

Kutullo Maibane (PhD)

Neutron light output spectrum measured at 0° with BC501A for a 66 MeV proton beam on 8.0 mm Li target

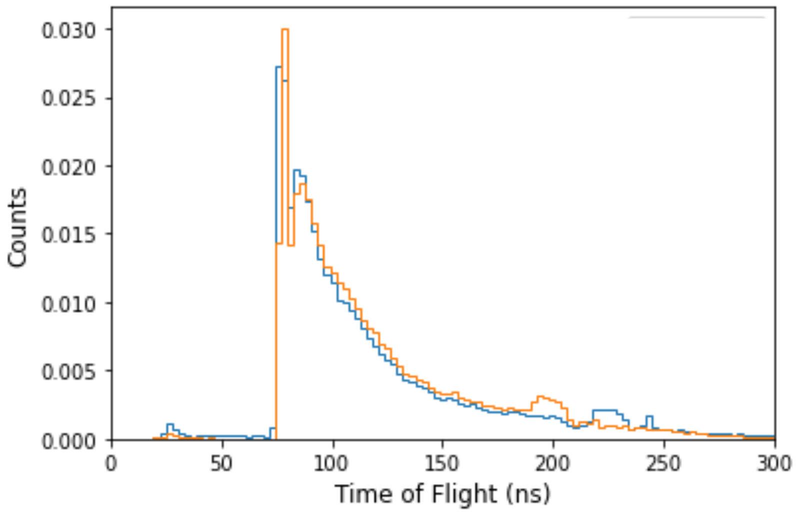


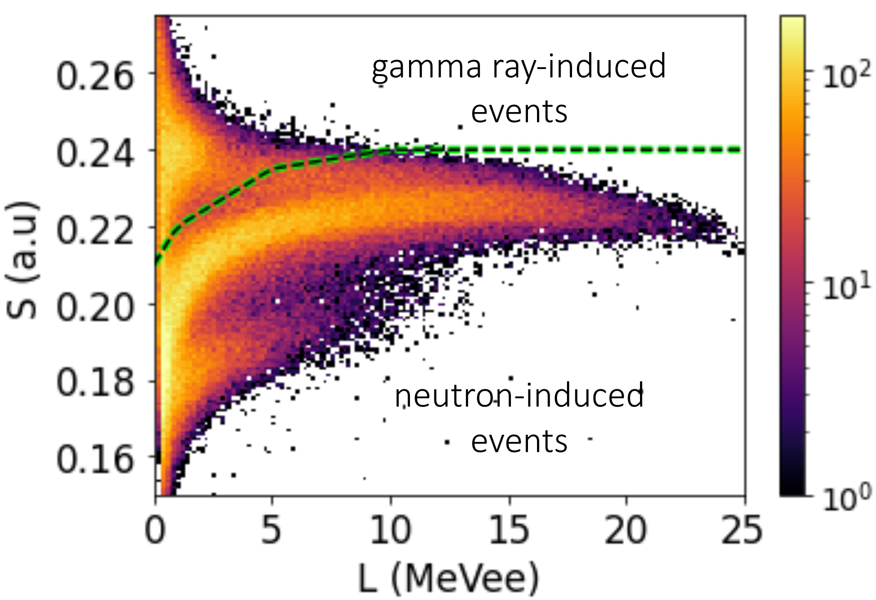



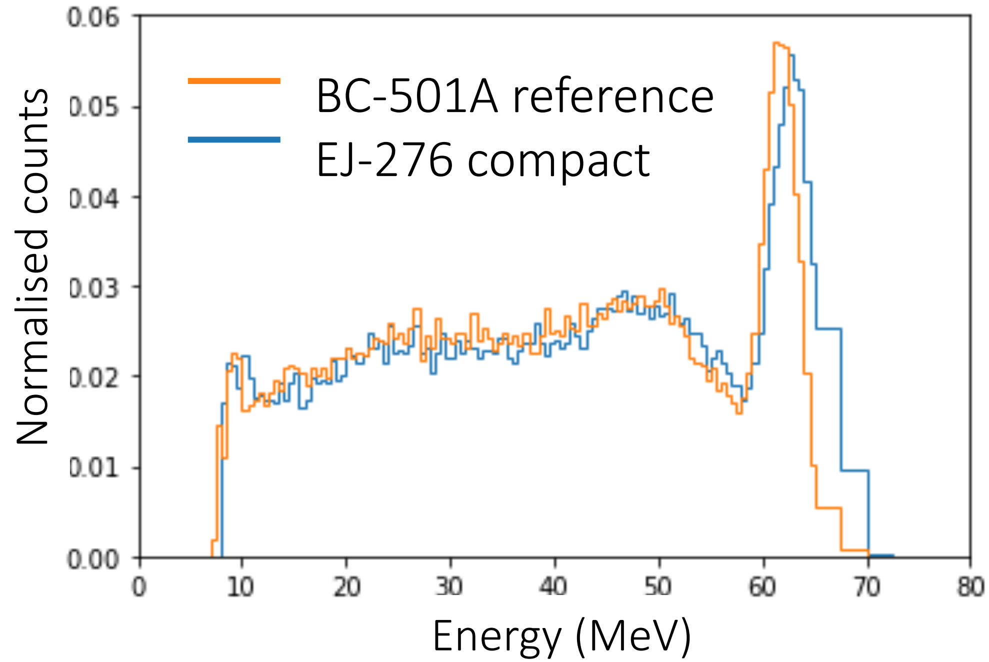



# Time of flight measurement of neutrons produced by a 66 MeV proton beam irradiating an 8.0 mm $^{nat}$Li target. (**EJ-276** at 8.00 m from the target at 16$^{o}$).

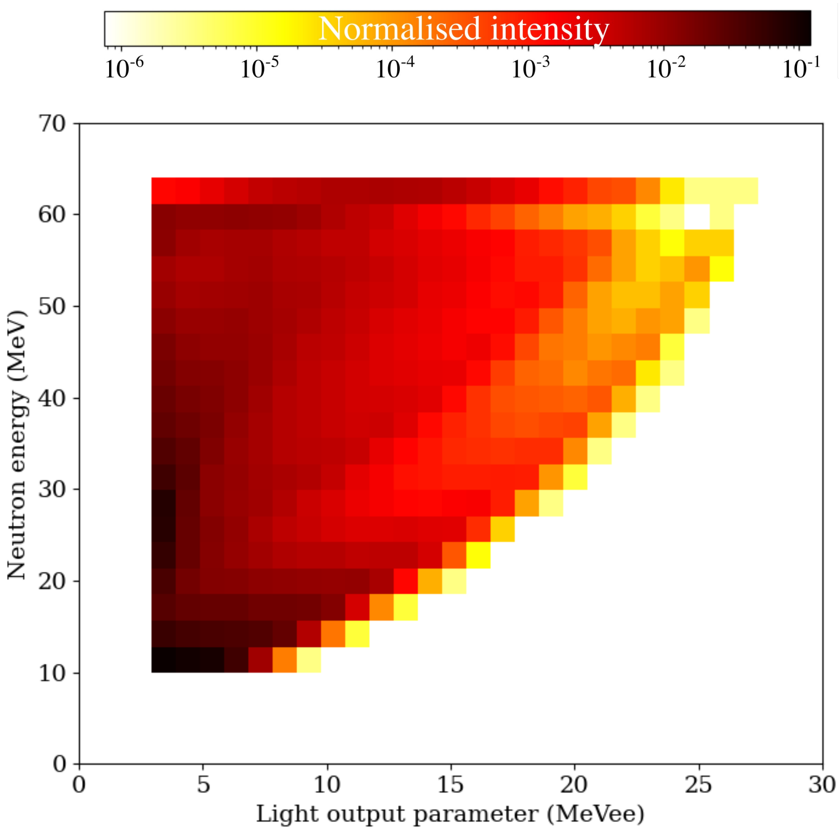
Erin Jarvie (MSc)

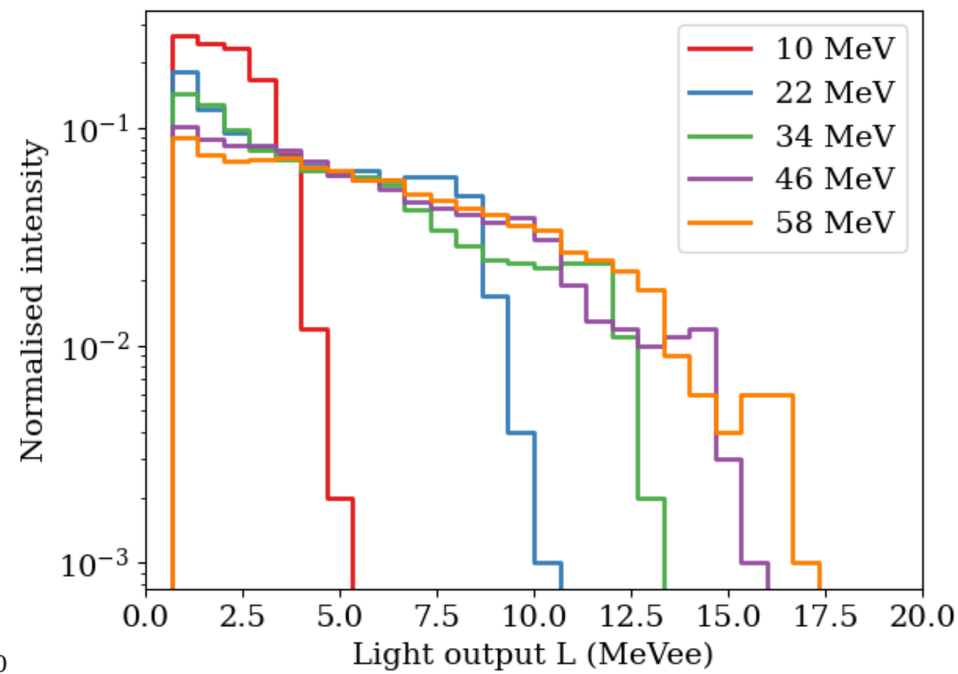


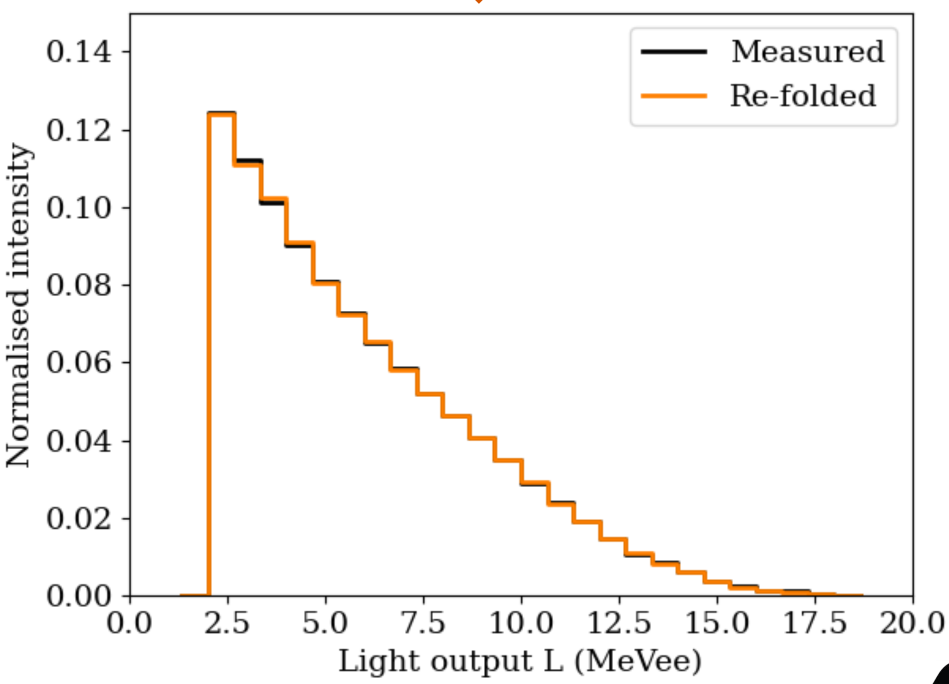

# Measured light output spectra for neutron energies between 10 - 65 MeV, selected by time-of-flight with EJ-276.

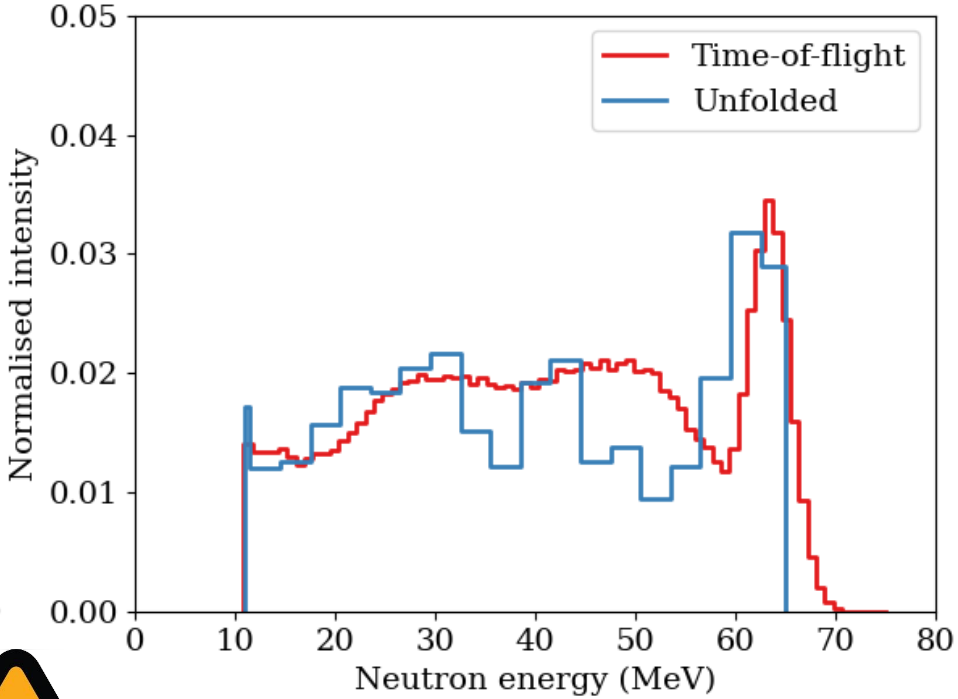



# Spectrum unfolding with measured detector response functions

Neutron light output spectrum measured at 16$^{o}$ with EJ-276 for a 66 MeV proton beam on 8.0 mm Li target




# Summary

- Detector response functions were measured at the iThemba LABS fast neutron facility using time-of-flight between 10 - 65 MeV for the reference BC501A and EJ276 detector systems.
- Unfolded energy spectra comparable to those measured by time-of-flight.
- Compact spectrometer design update underway, but very promising for fast neutron spectroscopy outside of the laboratory!
- Further measurements up to 200 MeV planned, with improved statistics to extend range of applications.

# Thank you!

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