Compact neutron spectrometers for aviation and space applications

Miles Kidson

Andy Buffler & Tanya Hutton

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UNIVERSITY OF CAPE TOWN

MeASURe
Metrological and Applied Sciences University Research Unit

n lab

François Trompier

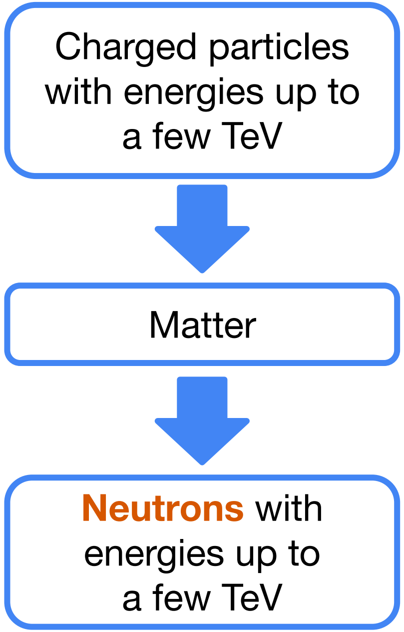
ASNR
Autorité de sûreté nucléaire et de radioprotection

Workshop on Advanced Nuclear Science and Technology Techniques ANSTT6

NRF-iThemba LABS, Cape Town

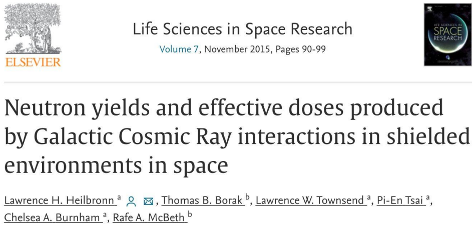
18-22 May 2026

The challenge: high energy neutrons in space


Charged particles with energies up to a few TeV

Matter

Neutrons with energies up to a few TeV


ELSEVIER

Life Sciences in Space Research

Volume 7, November 2015, Pages 90-99

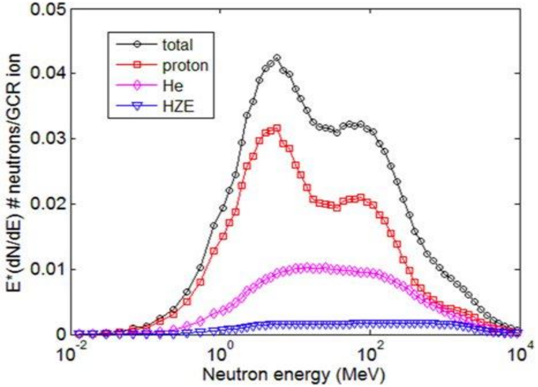
Neutron yields and effective doses produced by Galactic Cosmic Ray interactions in shielded environments in space

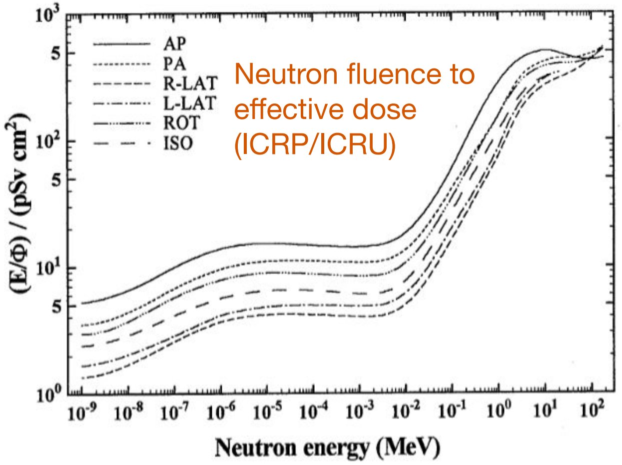
Lawrence H. Heilbronn [a], Thomas B. Borak [b], Lawrence W. Townsend [a], Pi-En Tsai [a], Chelsea A. Burnham [a], Rafe A. McBeth [b]

- Primary cosmic radiation

- Shielding
- Human body
- Atmospheres
- Regolith

GCR → 2.7 g/cm^2 aluminium




Neutron fluence to effective dose (ICRP/ICRU)

Neutron dose depends on the energy spectrum, so spectral measurements are necessary

The challenge: high energy neutrons in aviation

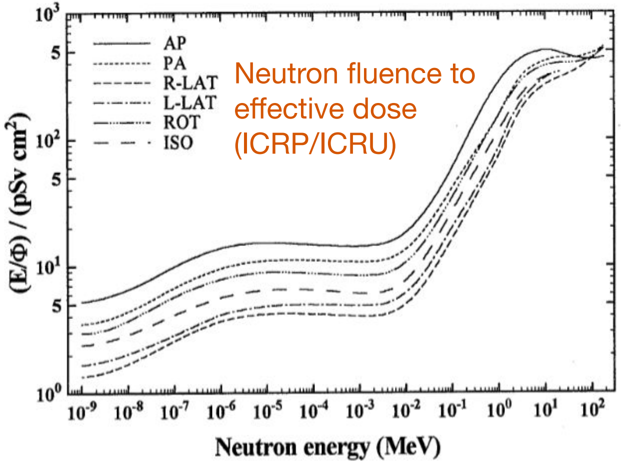
Charged particles with energies up to a few GeV

- Primary cosmic radiation

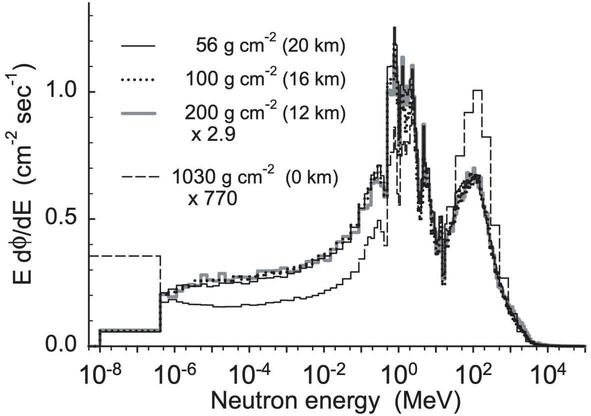
Matter

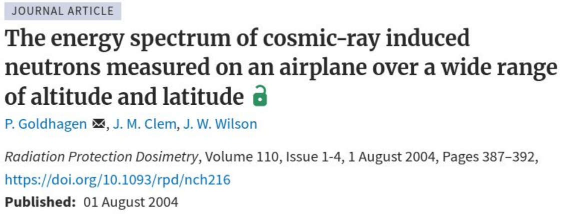
- Atmosphere
- Aircraft materials

Neutrons with energies up to a few GeV



Neutron fluence to effective dose (ICRP/ICRU)





JOURNAL ARTICLE

The energy spectrum of cosmic-ray induced neutrons measured on an airplane over a wide range of altitude and latitude

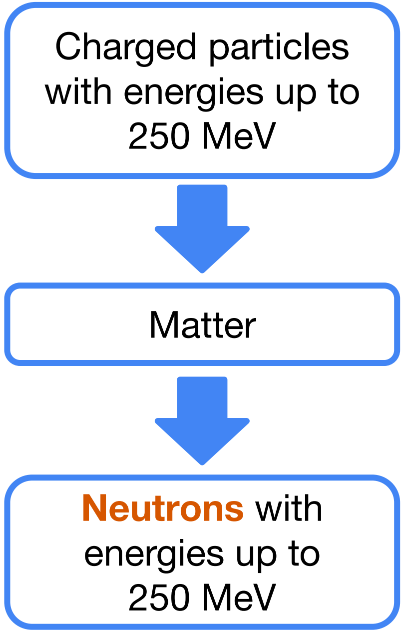
P. Goldhagen, J. M. Clem, J. W. Wilson

Radiation Protection Dosimetry, Volume 110, Issue 1-4, 1 August 2004, Pages 387–392, https://doi.org/10.1093/rpd/nch216

Published: 01 August 2004

Neutron dose depends on the energy spectrum, so spectral measurements are necessary

The challenge: high energy neutrons in proton therapy



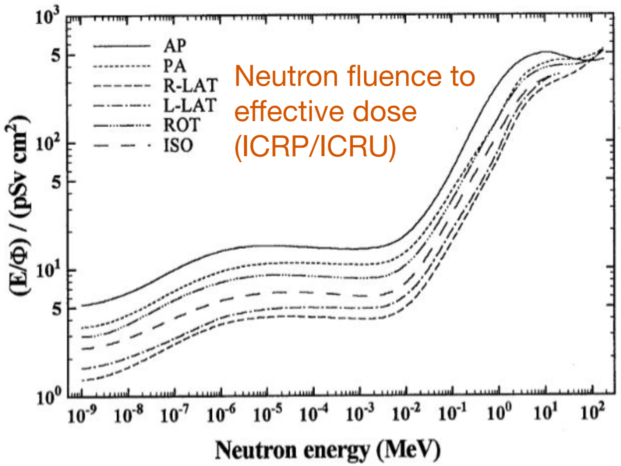
Charged particles with energies up to 250 MeV

Matter

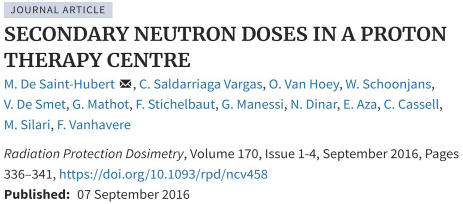
Neutrons with energies up to 250 MeV

- Protons

- Shielding
- Human body



Neutron fluence to effective dose (ICRP/ICRU)



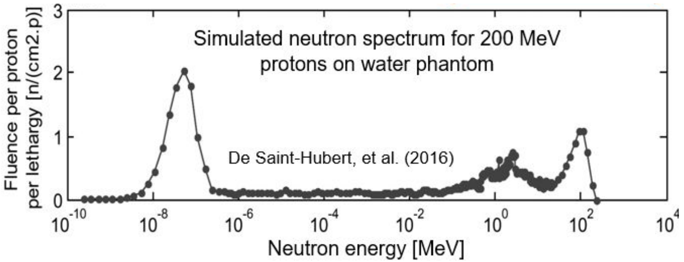
JOURNAL ARTICLE

SECONDARY NEUTRON DOSES IN A PROTON THERAPY CENTRE

M. De Saint-Hubert ✉, C. Saldarriaga Vargas, O. Van Hoey, W. Schoonjans, V. De Smet, G. Mathot, F. Stichelbaut, G. Manessi, N. Dinar, E. Aza, C. Cassell, M. Silari, F. Vanhavere

Radiation Protection Dosimetry, Volume 170, Issue 1-4, September 2016, Pages 336–341, https://doi.org/10.1093/rpd/ncv458

Published: 07 September 2016



Simulated neutron spectrum for 200 MeV protons on water phantom

De Saint-Hubert, et al. (2016)

Neutron dose depends on the energy spectrum, so spectral measurements are necessary

Neutrons in aviation

Commercial aircraft cruise at 9–12 km with reduced atmospheric shielding.

Exposure driven by:

- Galactic Cosmic Rays (GCRs)
- Solar Energetic Particles (SEP)

a

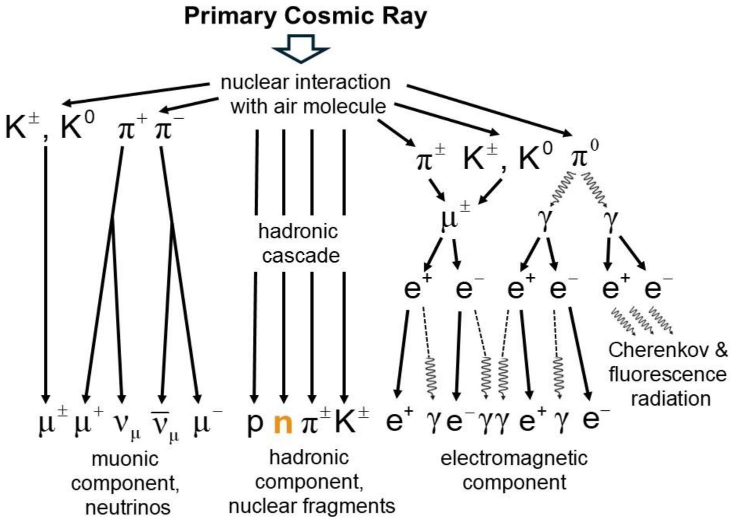
Dose contribution dominated by:

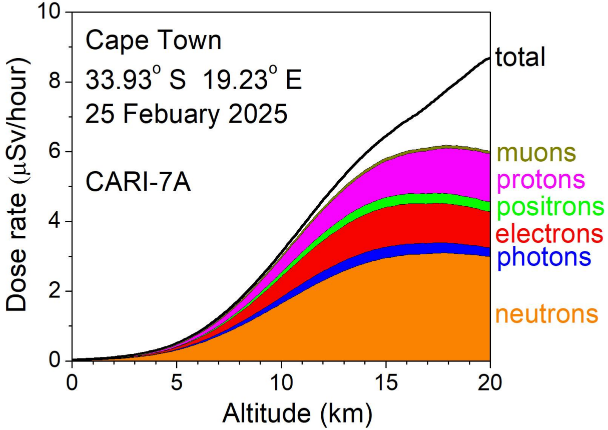
- Secondary neutrons
- High energy photons

Current status:

- Model-based (e.g. route + solar indices)
- Sparse airborne neutron data

Neutrons dominate dose uncertainty and they are the most difficult component to measure.



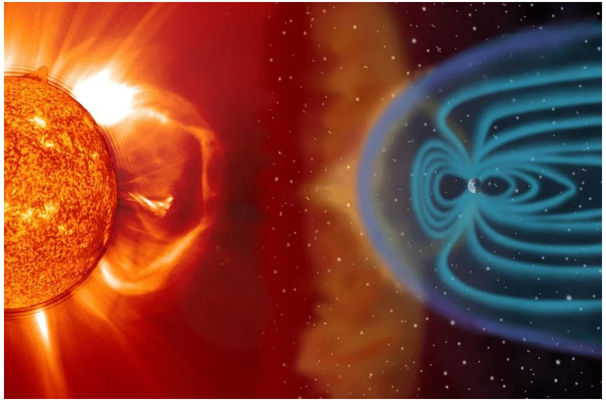


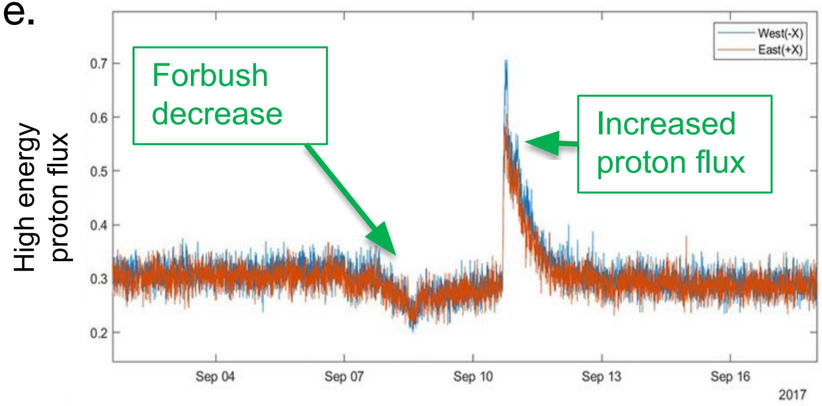
Space weather at flight altitude

Coronal mass ejections and solar flares impact the radiation field at high altitude.

- Enhanced interplanetary magnetic field
  → temporary reduction in GCR intensity (Forbush decrease).
- May be accompanied by increased solar energetic particle flux.
  → neutron-dominated dose increase at altitude.

Space weather produces time-dependent and energy-dependent changes in the neutron field, which cannot be fully inferred from ground-based monitoring alone.





10.1029/2022SW003155

Design requirements for a neutron spectrometer in aviation

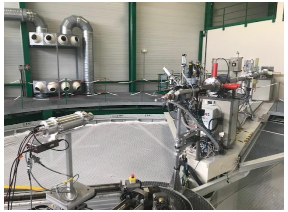
Compact	**Silicon photomultipliers**
Safe to operate	**Plastic scintillator** **Silicon photomultipliers**
Neutron/gamma ray discrimination	**PSD-capable plastic scintillator**
Sensitive over a large range (1-120 MeV)	**Plastic scintillator with measured response functions**
Flexible geometries	**Plastic scintillator**
Spectral capability in situ	**Spectral unfolding with measured response functions**

Previous work

- Detector concept validated below 20 MeV.
- Monoenergetic response functions measured at PIAF (PTB, Germany) and AMANDE (ASNR, France).
- Energy range limited by scintillator size (upper) and efficiency simulation constraints (lower).

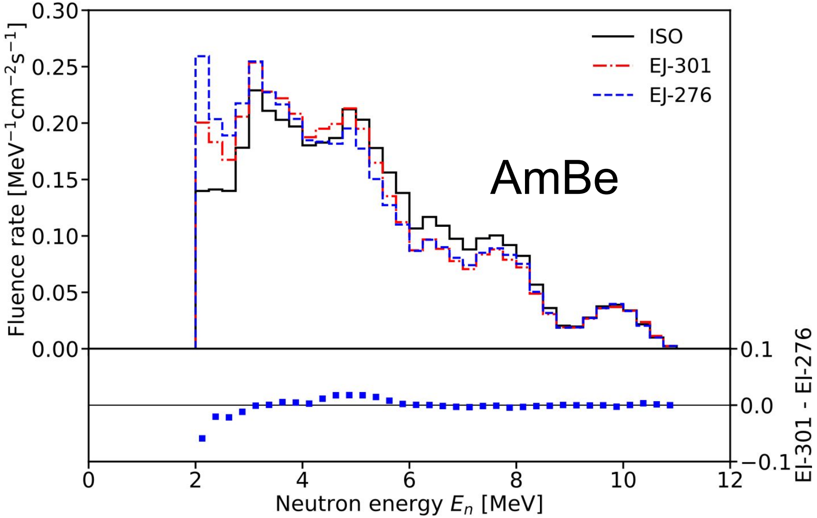
PTB
Physikalisch-Technische Bundesanstalt
National Metrology Institute

PIAF



ASNR Autorité de sûreté nucléaire et de radioprotection

AMANDE



Research goals

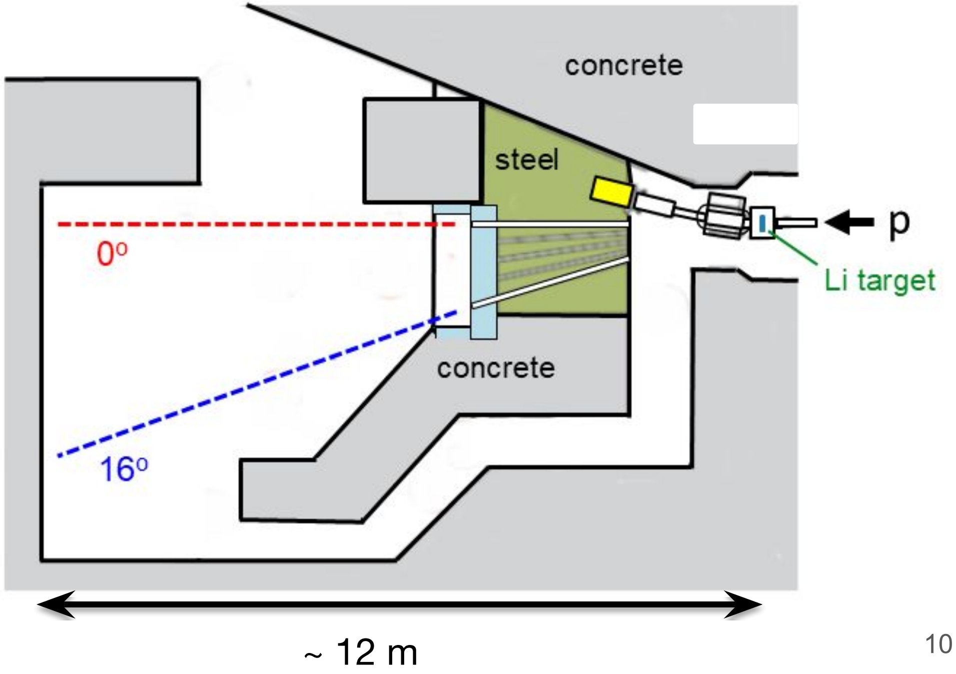
The primary aim of this research is to develop a self-contained, compact high energy neutron spectrometer.

- Extend detector prototype to higher energies by increasing scintillator size.
- Combine simulation and measurement for response functions up to 120 MeV.
- Develop autonomous signal processing and data acquisition system.
- Characterise performance at fast- and high-energy reference neutron facilities.
- Evaluate stability under aviation-relevant temperature, vibration, and pressure conditions.

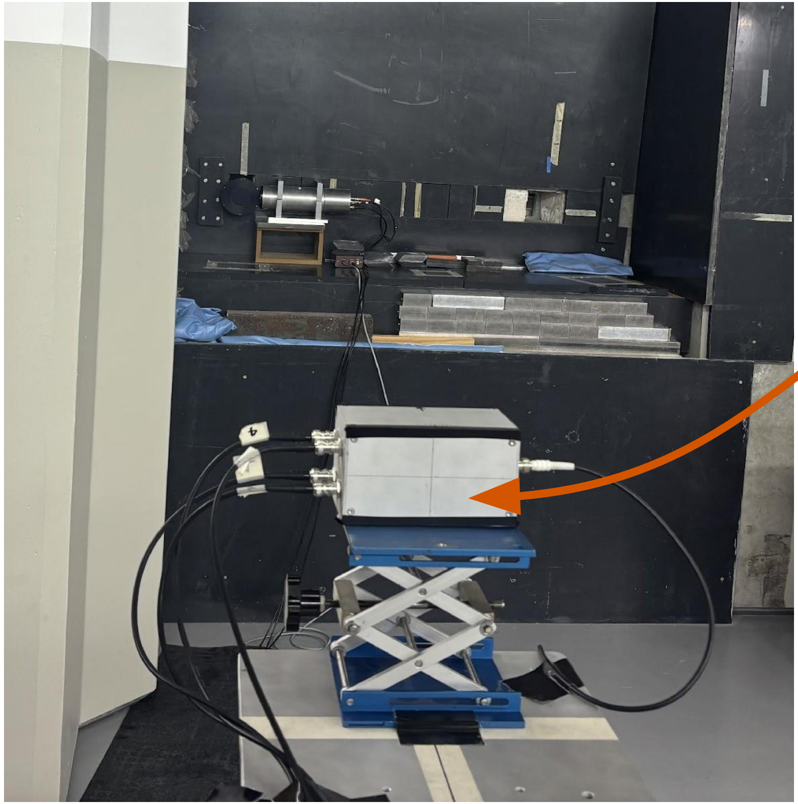
High energy neutron beam facility at iThemba LABS

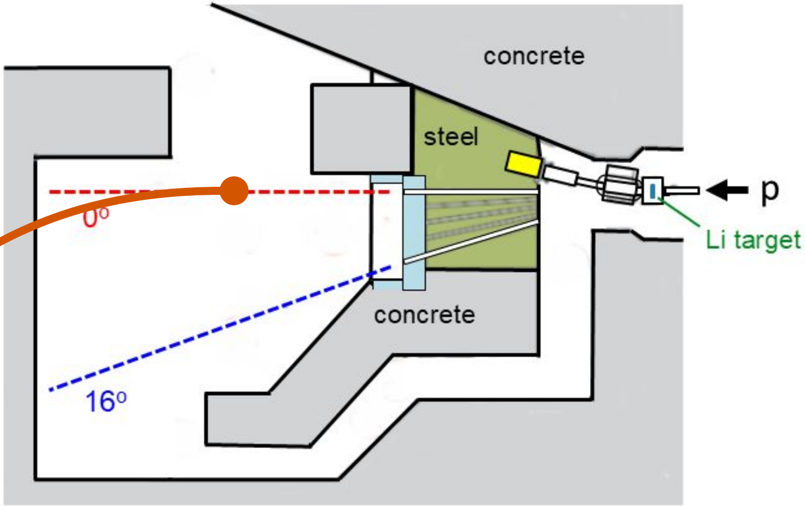
Cape Town, South Africa

- k = 200 cyclotron.
- Neutrons via Li(p,n).
- Ns-pulsed beams with ToF.
- Quasi-monoenergetic high energy neutron beams 30-200 MeV.



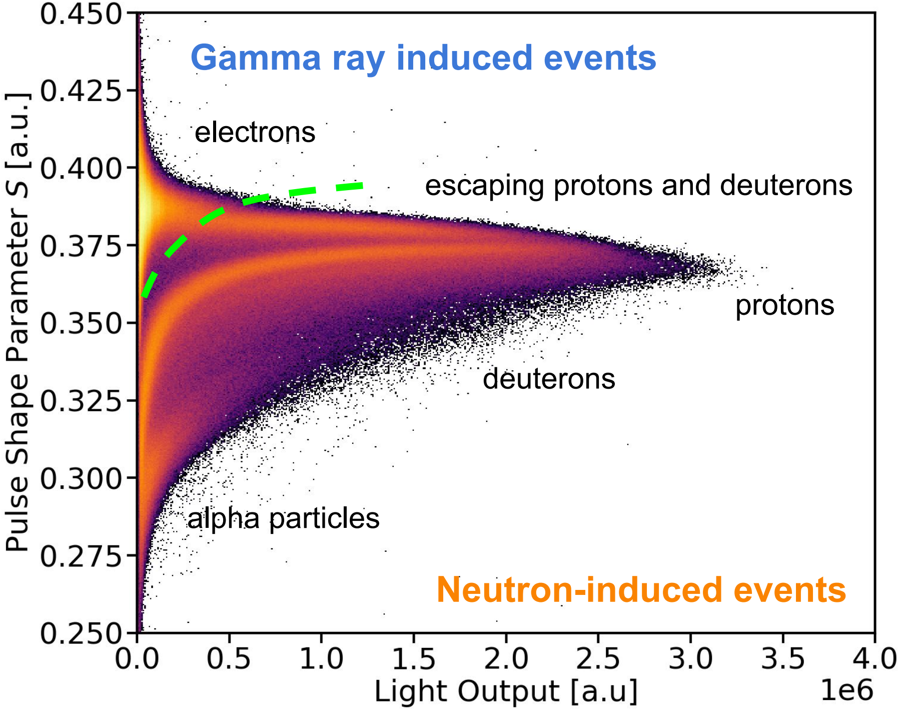
Characterisations at iThemba LABS, September 2025
(E_p = 150 MeV, 8.0 mm Li target, $I \approx$ 3 nA)





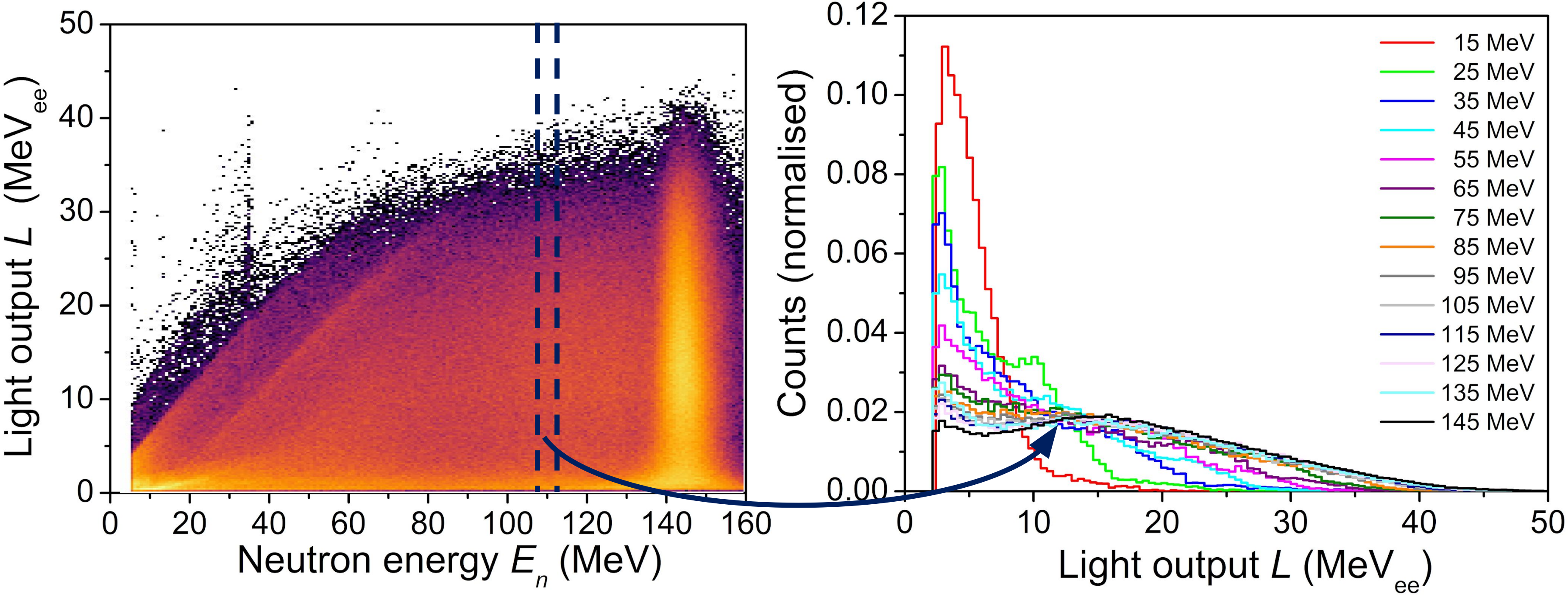
The detector was positioned at 8.0 m from the neutron production target at 0°.

Characterisations at iThemba LABS, September 2025 (E_p = 150 MeV, 8.0 mm Li target, $I \approx 3$ nA)



September 2025 (Preliminary)

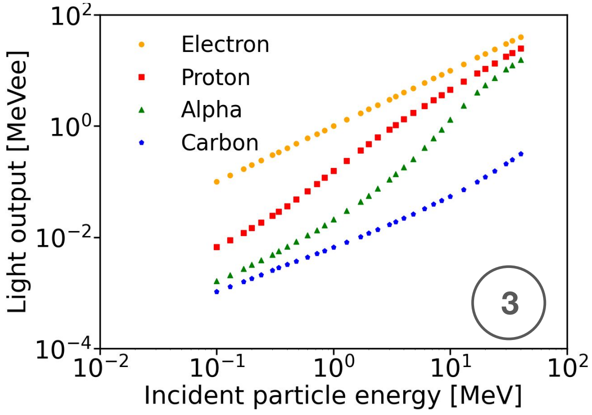
Characterisations at iThemba LABS, September 2025
(E_p = 150 MeV, 8.0 mm Li target, $I \approx$ 3 nA)

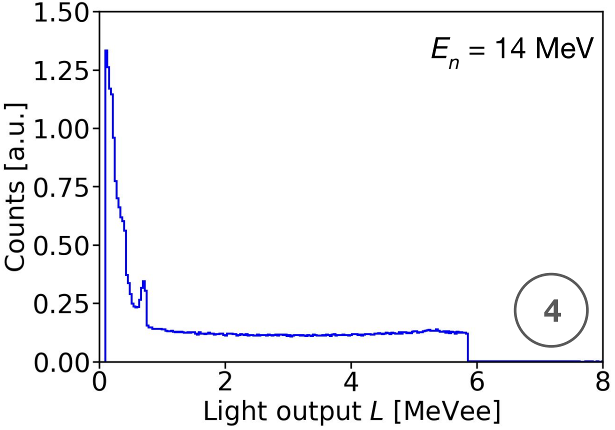


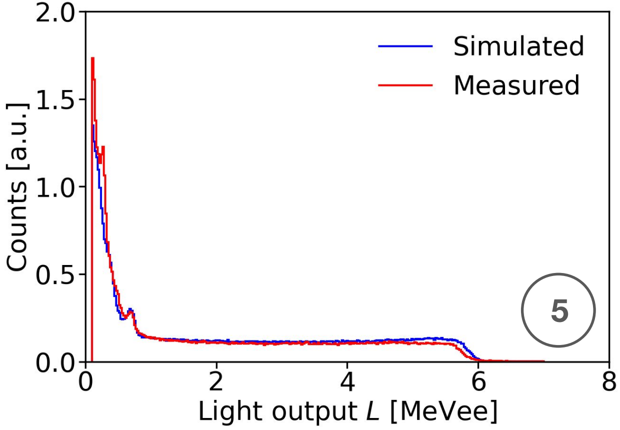
Quasi-monoenergetic detector response functions are obtained by **time-of-flight** selection of the neutron energy, illustrated here for 115 MeV (ΔE = 10 MeV).

Simulation of response functions with Geant4

1. Monoenergetic neutron interacts in plastic scintillator.
2. Energy deposition recorded for each recoil particle (step-wise).
3. Conversion to light output according to particle type and summed along total track.
4. Combine multiple events produce light output spectrum.
5. Gaussian broadening applied event-by-event to reproduce realistic result.







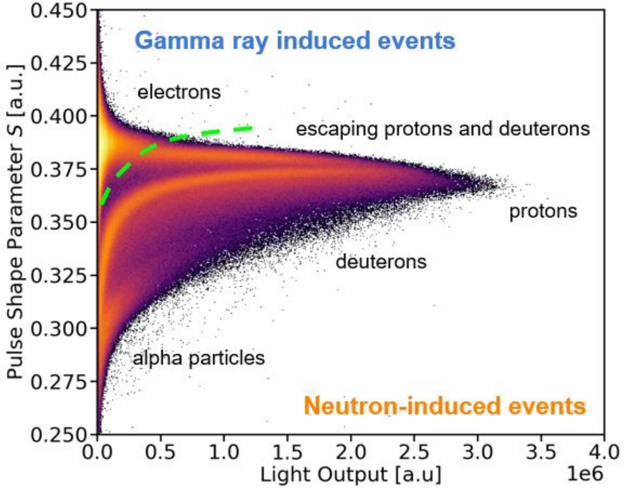
Extending simulations above 20 MeV

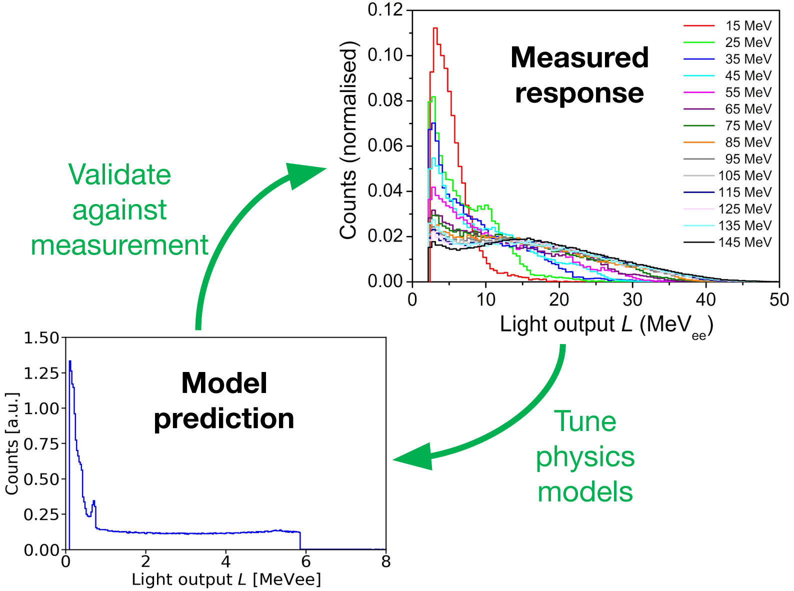
Above 20 MeV:

- Transition from data → model driven transport
- More ^{12}C reaction channels accessible
- Inelastic processes dominate

Detector response harder to predict:

- Multiple recoil particles per event
- Partial energy deposition increases





Simulations are insufficient above 20 MeV in isolation

- Poor knowledge of ^{12}C reaction cross sections
- Model-driven transport largely unverified

High-energy measurements are essential to generate reliable response functions

Summary

- High-energy laboratory prototype tested up to 150 MeV (time-of-flight) at iThemba LABS.
- Simulated detector response functions validated below 20 MeV.

Ongoing

- Extend validation of simulations above 20 MeV using measured response functions.
- Development of a compact on-board DAQ (PSD and spectrometry).

Future work

- Additional characterisation in aviation-relevant neutron fields.
- Flight-altitude measurements and long-term operation.
- Integration into citizen science projects, e.g. Cosmic On Air.

COSMIC ON AIR A Citizen Science approach to hunting Solar Eruptive Phenomena at flight altitudes

François Trompier[1], Andy Buffler[2], Carine Briand[3], Tanya Hutton[2], Miles Kidson[2], Antoine Dreux[1], Aidan Gebbie[2], Véronique Lejeune[1]

[1] LDRI, Autorité de Sûreté Nucléaire et de Radioprotection, 92260 Fontenay-aux-Roses, France.
[2] Department of Physics, University of Cape Town, 7700 Rondebosch, South Africa.
[3] LESIA, Observatoire de Paris-PSL, 92295 Meudon, France.

Cosmic On Air is a Citizen Science project which aims to increase coverage of measurements of cosmic radiation on board aircraft in the search of solar eruptive phenomena. A number of low-cost, compact, and connected radiation monitors are available to the public for purchase, and the data measured during flights are uploaded to an open data repository for analysis.

Dosimetry of aircrew is routinely achieved using numerical approaches validated by measurements made on board aircraft. However, in cases of randomly occurring solar eruptive phenomena, which can produce a burst of sufficiently energetic Solar Particle Events to be classified as a Ground Level Event (GLE), the dose rates at flight altitudes can be significantly increased. Current dosimetry models for GLEs cannot be easily validated due to the very few on-board measurements during such phenomena.

Participate in this project

- Get a sensor.
- Fly on a plane and measure!
- Analyse your data with our Python tools (great for high school, college and university projects).
- Contribute to science: upload your data on our website, or email the file to us.
- Be a co-author on the scientific paper with the first measurement of a solar flare.

Present developments

- Upgrades to the OpenRadiation App.
- Improvements to analysis tools for all detectors.
- Educational materials for school and college projects.
- New compact detector for neutron radiation.

Connect with us

www.cosmic-on-air.org
cosmiconair@gmail.com

@COSMICONAIR

cosmic_on_air

open radiation
www.openradiation.org

Sensors

bGeigieZen
(or bGeigieNano)
www.safecast.org
Pancake GM;
Onboard GPS;
microSD card

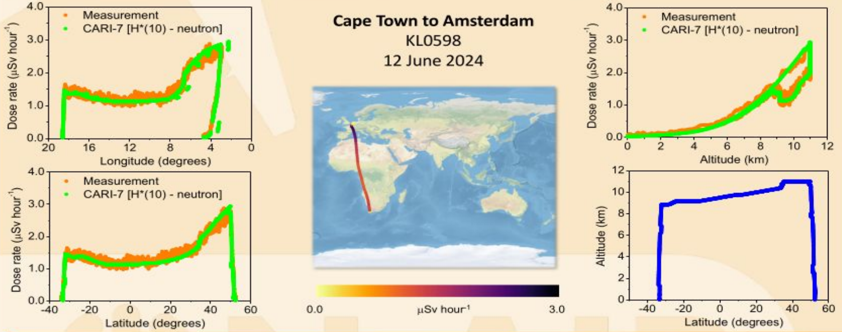
Radiacode 103
(or 102 or 110)
www.radiacode.com
Scintillation detector;
Internal memory;
Phone app

GMC-800
(or GMC-500+ or similar)
www.gqelectronicsllc.com
Geiger counter;
Internal memory;
Desktop viewer

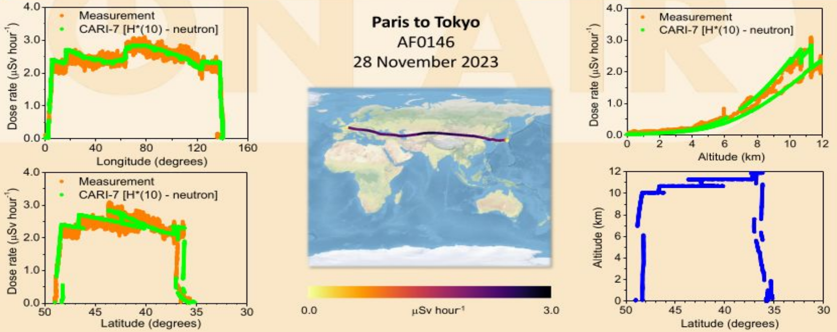
Recent measurements

- Measurements made on two flights are shown, blended with flight data from FlightAware.
- Calibration coefficients for dose rate have been derived for these sensors using in-flight measurements with reference detectors (e.g. Hawk TEPC).
- CARI-7 is a code developed by the Federal Aviation Administration* to calculate the dose rate ($H^*(10)$) as a function of radiation type, geographic location, altitude, and known fluctuations in solar activity.
- Since the current sensors are insensitive to neutron radiation, the neutron contribution is subtracted from the total dose before comparison with measurement.

*https://www.faa.gov/data_research/research/med_humanfacs/aeromedical/radiobiology/cari7



Cape Town to Amsterdam
KL0598
12 June 2024



Paris to Tokyo
AF0146
28 November 2023

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Thank you for your attention!
Questions?

References

L. H. Heilbronn et al., Neutron yields and effective doses produced by Galactic Cosmic Ray interactions in shielded environments in space, *Life sciences in space research*, Volume 7 (2015), Pages 90–99, doi: 10.1016/j.lssr.2015.10.005

P. Goldhagen et al., The energy spectrum of cosmic-ray induced neutrons measured on an airplane over a wide range of altitude and latitude, *Radiation Protection Dosimetry*, Volume 110, Issue 1-4 (2004), Pages 387–392, doi: 10.1093/rpd/nch216

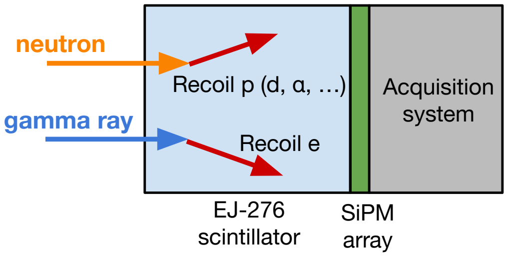
M. De Saint-Hubert et al., Secondary neutron doses in a proton therapy centre, *Radiation Protection Dosimetry*, Volume 170, Issue 1-4 (2016), Pages 336-41, doi: 10.1093/rpd/ncv458

A. D. P. Hands et al., A new model for nowcasting the aviation radiation environment with comparisons to in situ measurements during GLEs, *Space Weather*, Volume 20, Issue 8 (2022), doi: 10.1029/2022SW003155

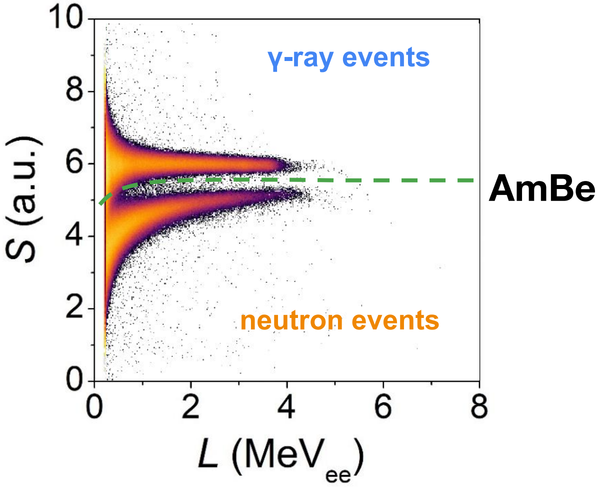
This workshop attendance is supported in part by the National Research Foundation of South Africa (Ref CSRP250306301626).

Backup slides!

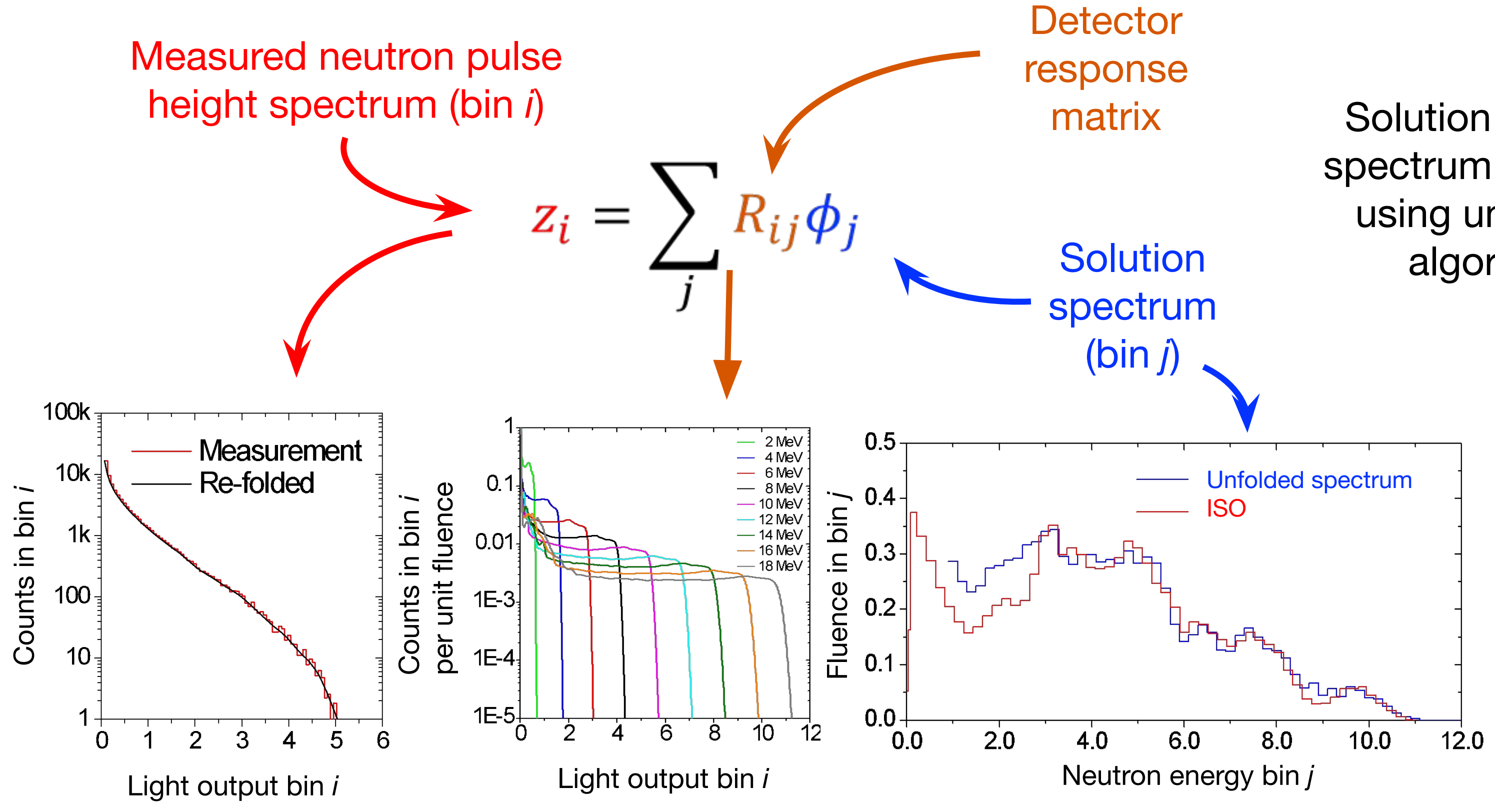
Detecting neutrons (and gamma rays)



- Neutrons interact with scintillators via elastic scattering and inelastic reactions.
- Recoiling particles (proton, alpha, ^{12}C, etc.) carry a fraction of the incident neutron energy depending on the reaction.
- Gamma rays interact primarily by Compton scattering, producing recoil electrons.
- Charged particles deposit energy via the Coulomb interaction, producing scintillation photons (~420 nm) proportional to the deposited energy.
- Scintillation light is detected by a silicon photomultiplier (SiPM), producing a voltage pulse amplitude proportional to the light output.
- The time characteristics of the pulse depend on particle type, allowing for pulse shape discrimination (in certain scintillators)



Spectrum unfolding



Measured neutron pulse height spectrum (bin *i*)

Detector response matrix

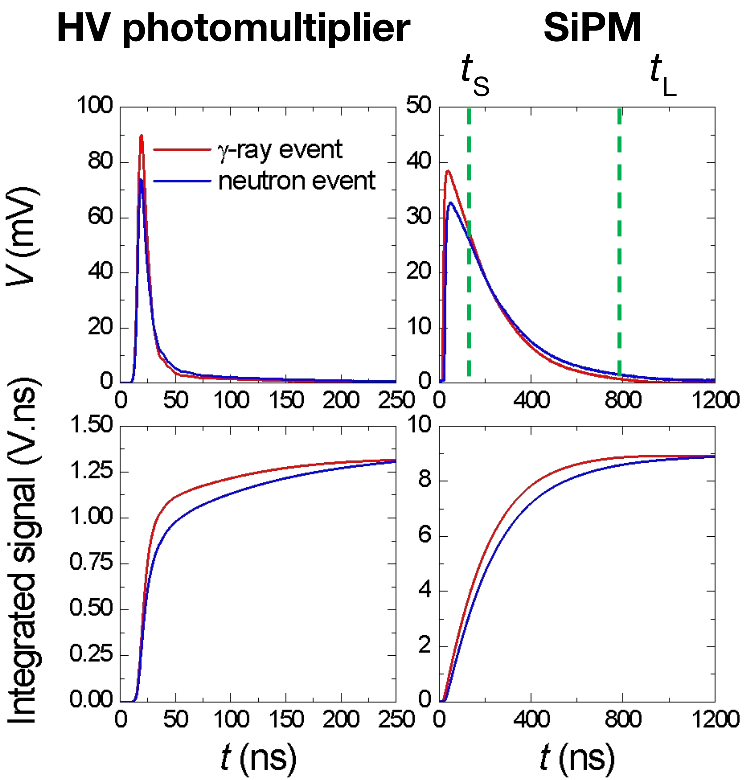
$$z_i = \sum_j R_{ij}\phi_j$$

Solution spectrum (bin *j*)

Solution neutron spectrum obtained using unfolding algorithm

The reliability of the reconstructed spectrum depends on accurate detector response functions, which are not well described by simulations **above 20 MeV and must be measured**.

Pulse Shape Discrimination

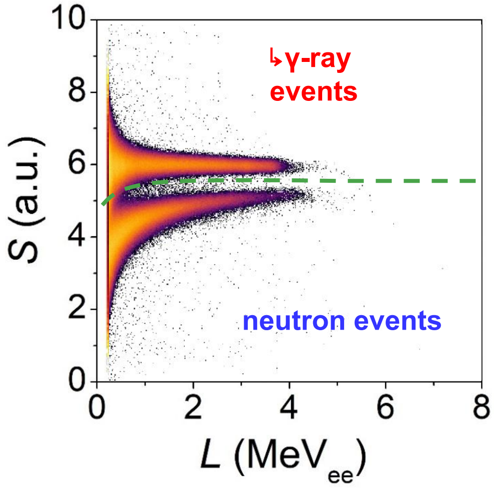


Light output parameter L

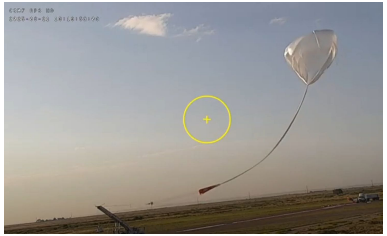
(long integral in $\mathrm{MeV_{ee}}$)

Pulse shape parameter S

$$S = k\,\frac{\text{short integral}}{\text{long integral}} + C$$



AmBe

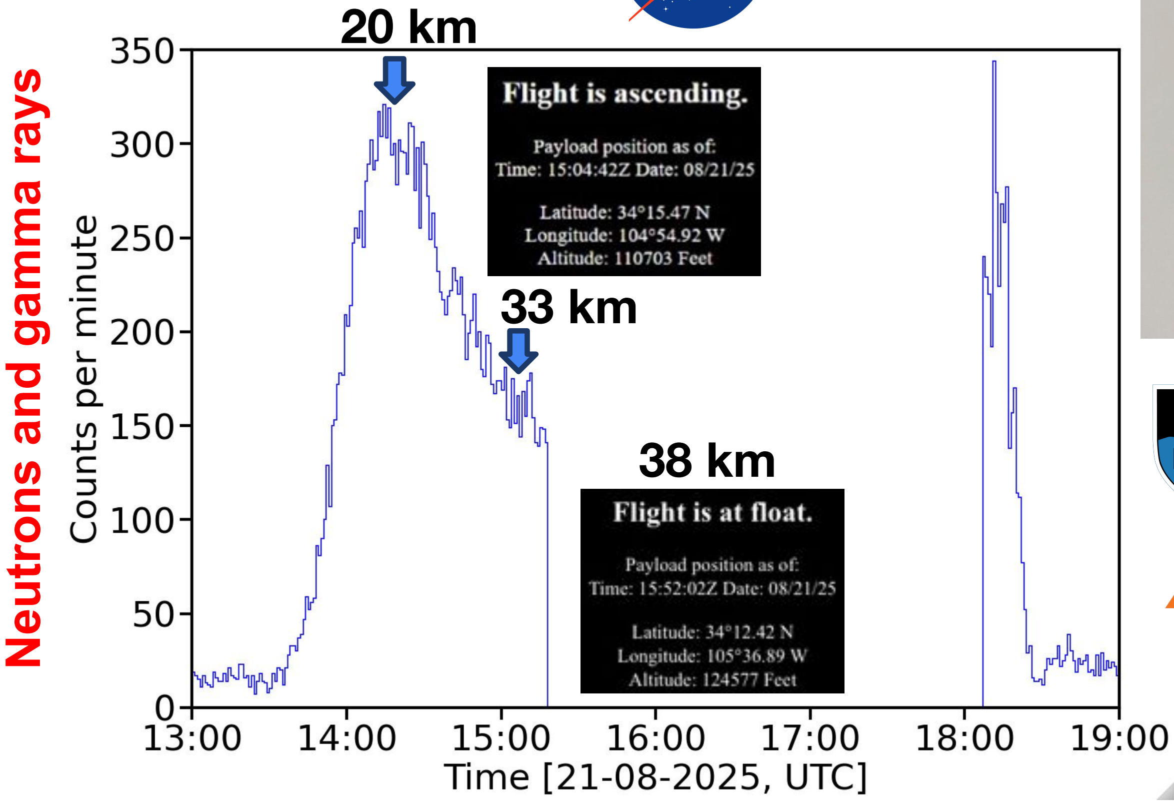



Flight is ascending.

Payload position as of:
Time: 14:15:09Z Date: 08/21/25

Latitude: 34°16.19 N
Longitude: 104°25.80 W
Altitude: 62281 Feet

Salter High Altitude Balloon Test Flight #752NT
21 August 2025



Flight is ascending.

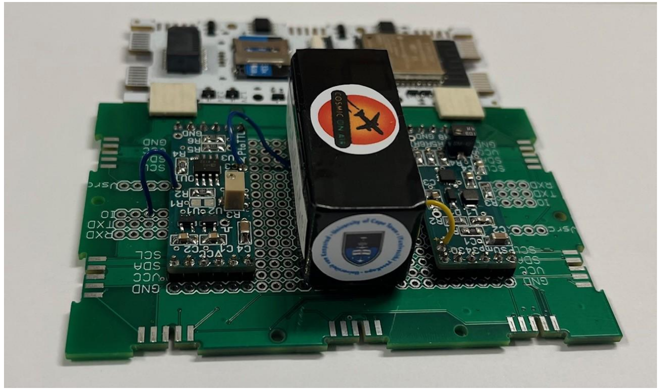
Payload position as of:
Time: 15:04:42Z Date: 08/21/25

Latitude: 34°15.47 N
Longitude: 104°54.92 W
Altitude: 110703 Feet

Flight is at float.

Payload position as of:
Time: 15:52:02Z Date: 08/21/25

Latitude: 34°12.42 N
Longitude: 105°36.89 W
Altitude: 124577 Feet



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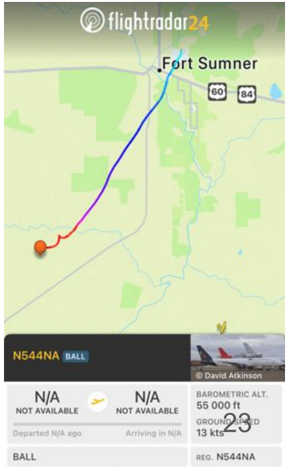
MAXIQ

COSMIC ON AIR



N544NA BALL

© David Atkinson

N/A
NOT AVAILABLE

N/A
NOT AVAILABLE

Departed N/A ago
Arriving in N/A

BAROMETRIC ALT.
55 000 ft

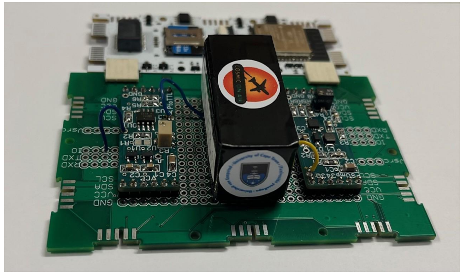
GROUND SPEED
13 kts

BALL

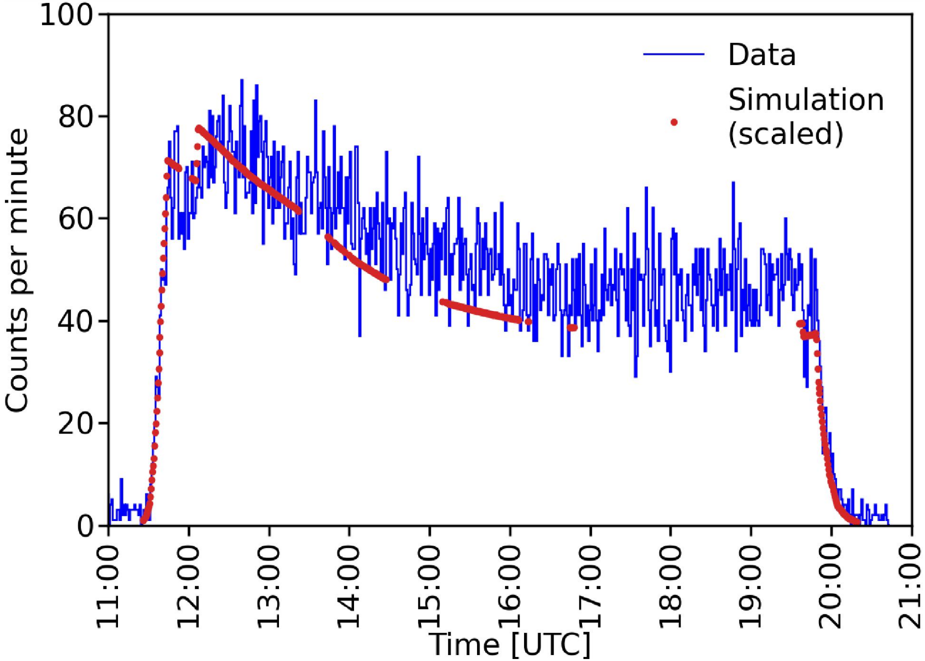
REG. N544NA

In-flight measurements

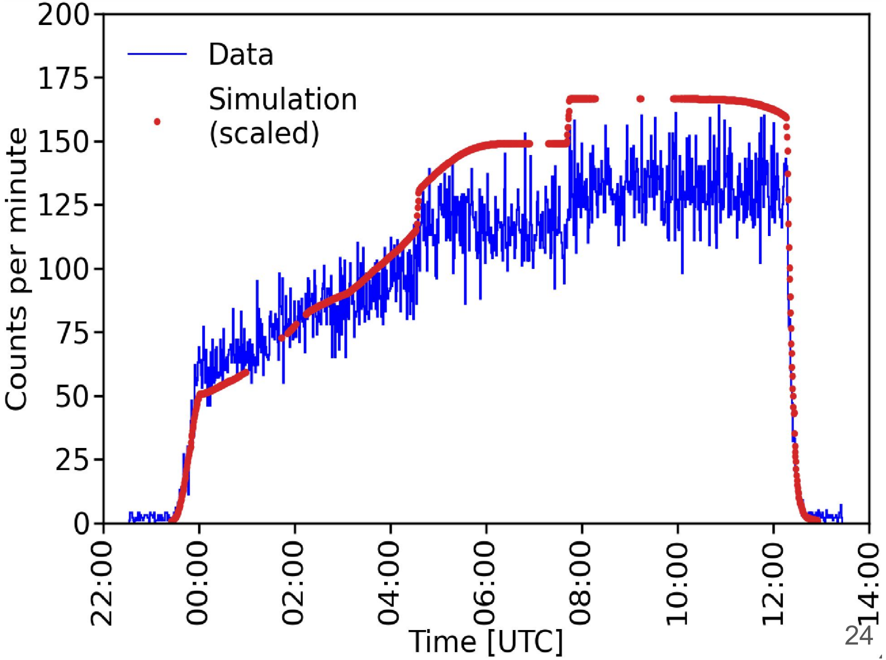
24 September 2025



EK773 Cape Town to Dubai

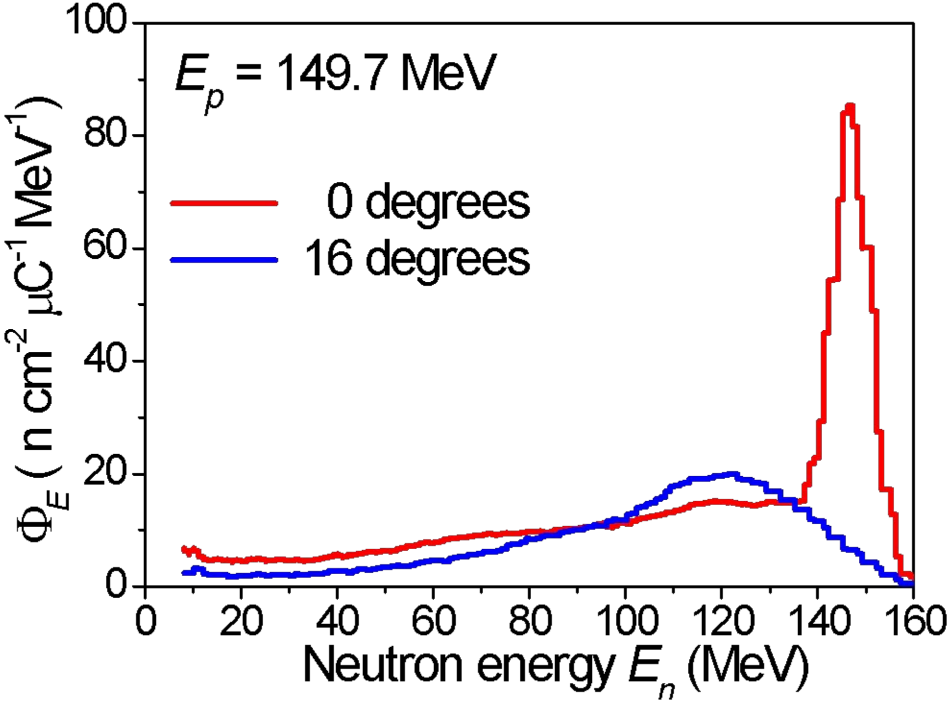


EK203 Dubai to New York



Energy spectra of neutrons produced by a proton beam of energy 150 MeV irradiating an 8.0 mm Li target

(measured with a 2” x 4” BC-501A reference detector at 8.00 m at 0 degrees).



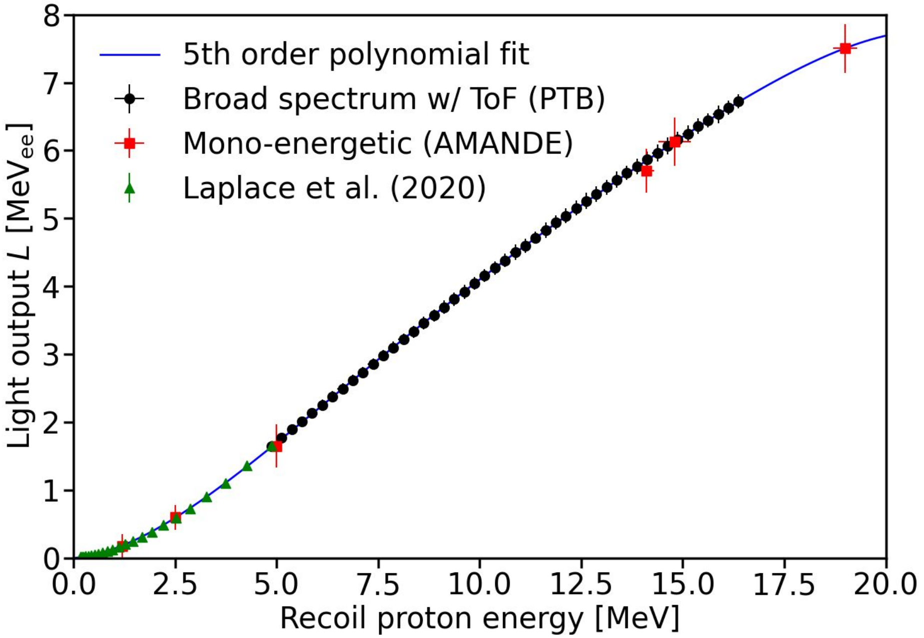
September 2025 (Preliminary)

Simulation of response functions below 20 MeV

Light output as a function of recoil proton energy must be measured due to nonlinearities arising from the detector components at high energies.

At low energies, measurements by Laplace et al. (2020) were used.

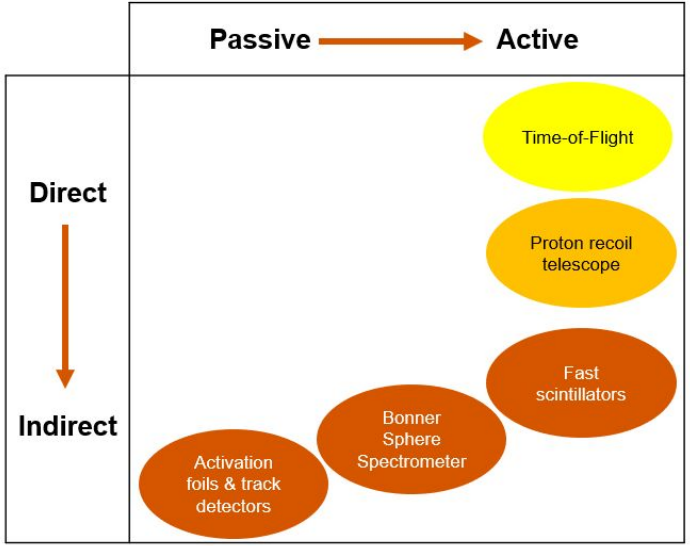
A fifth order polynomial was fit to the data, for smooth interpolation.

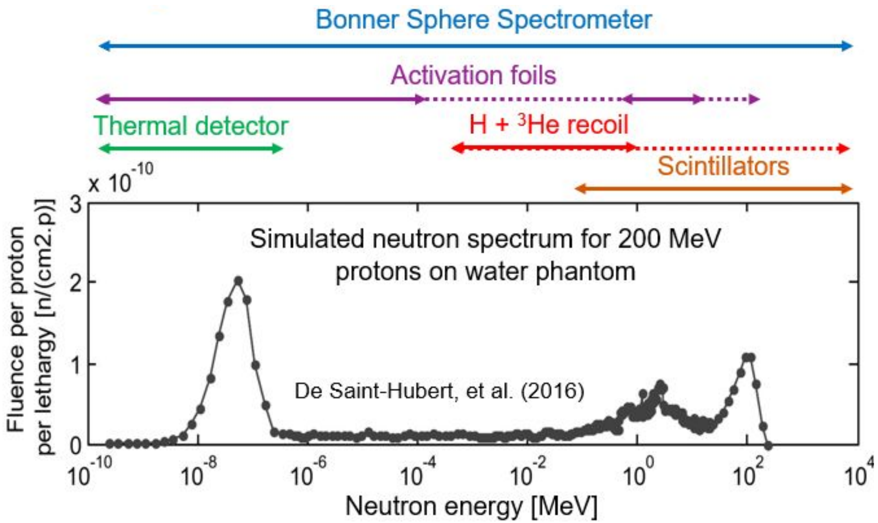


Detector systems for neutron spectrometry

A neutron spectrometer measures the energy distribution of neutrons, not just how many reach the detector.

Outside of the laboratory, this is achieved using spectrum unfolding techniques.





In unfolding-based systems, the neutron energy spectrum is reconstructed using calibrated detector response functions.