DEPARTMENT OF PHYSICS
UNIVERSITY OF CAPE TOWN
IYUNIVESITHI YASEKAPA • UNIVERSITEIT VAN KAAPSTAD

MeASURe
Metrological and Applied Sciences University Research Unit

Elemental characterization of bulk materials using fast neutron beams at the n lab.

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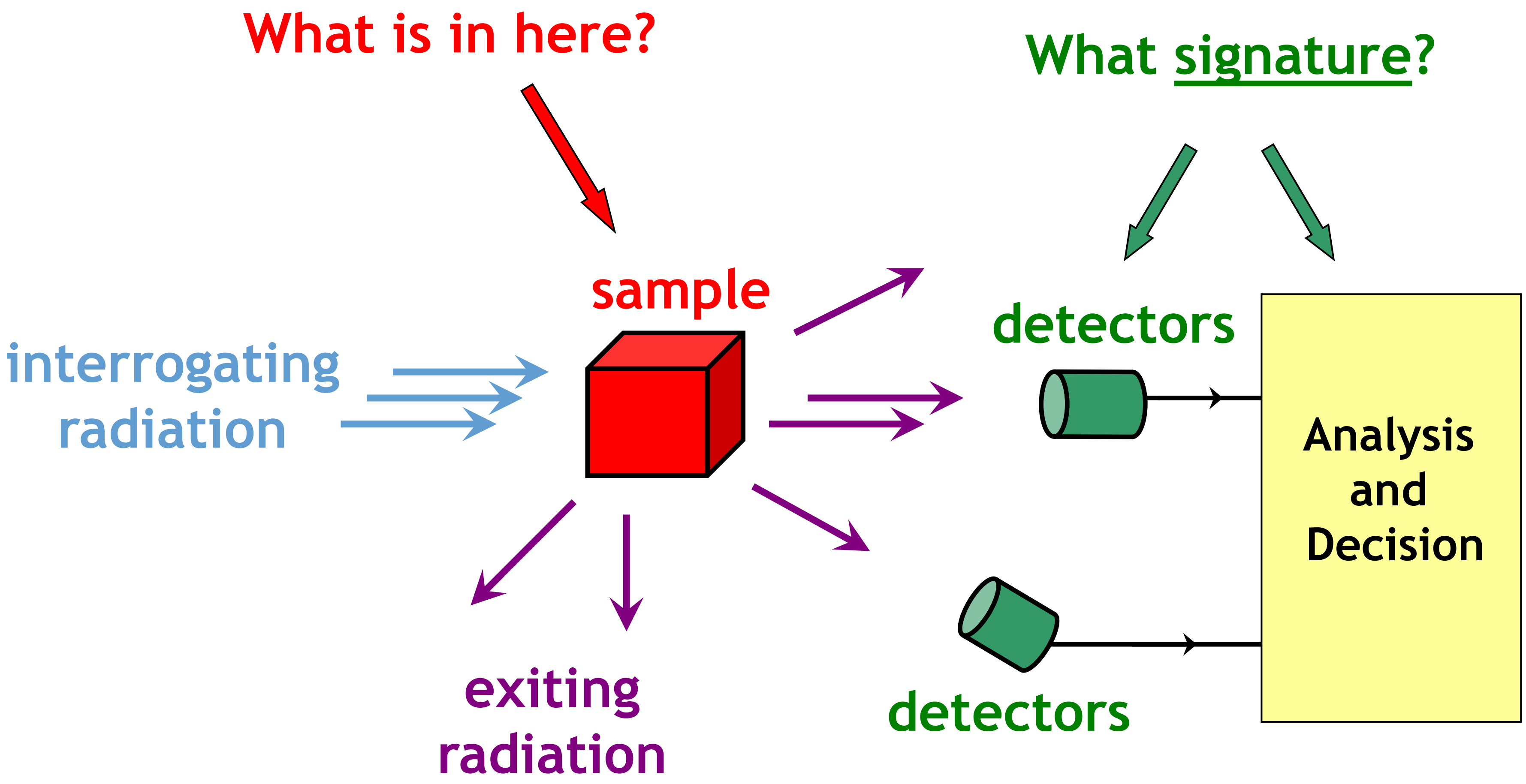
Andy Buffler, Tanya Hutton and Zina Ndabeni

Norfolk, Virginia
AccelApp'24

Radiation-based techniques for elemental characterization



Radiation-based techniques for coal analysis

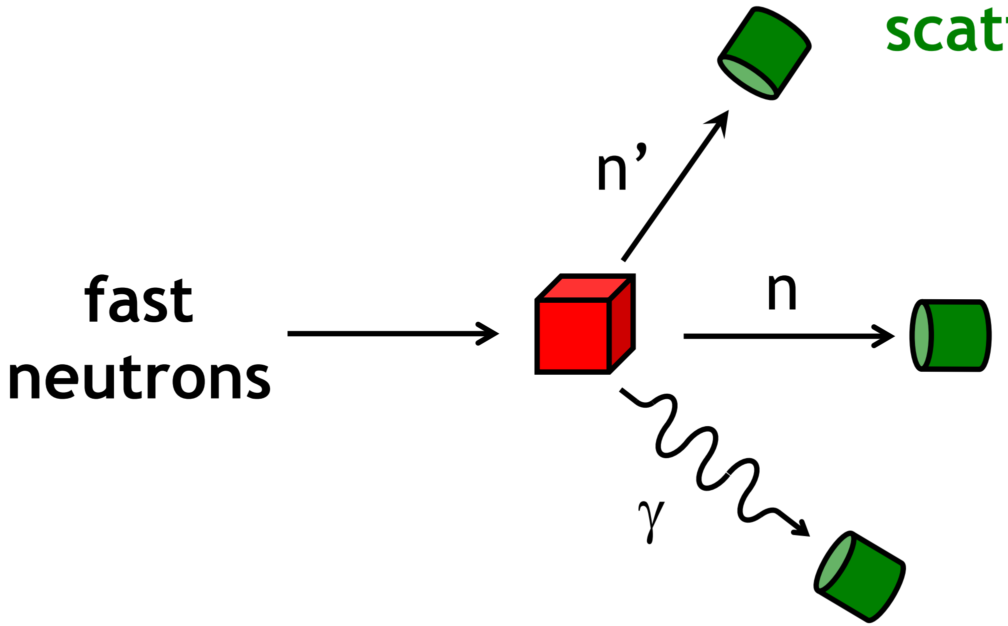
- **Coal** plays a central role in the electrical power production in South Africa.
- Knowledge of the elemental composition of coal (e.g. on belt within the processing cycle) has high economic and environmental value.
- Commonly used techniques for analysis are destructive, e.g. x-ray diffraction and x-ray absorption spectroscopy.

Element	% by mass
Carbon	77-80
Hydrogen	4-5
Oxygen	12-15
Nitrogen	2-3
Sulphur	1-2
Ash (SiO_2, Al_2O_3, Fe_2O_3, …)	

Matjie, R.H., et al., *Determination of mineral matter and elemental composition of individual macerals in coals from Highveld mines*, J. S. Afr. Inst. Min. Metall., 116:2 (2016).

Aim of this work: to develop a non-destructive multimodal technique using fast neutron beams for the elemental characterization of coal and other materials in bulk.

Fast neutron-based techniques for elemental characterization

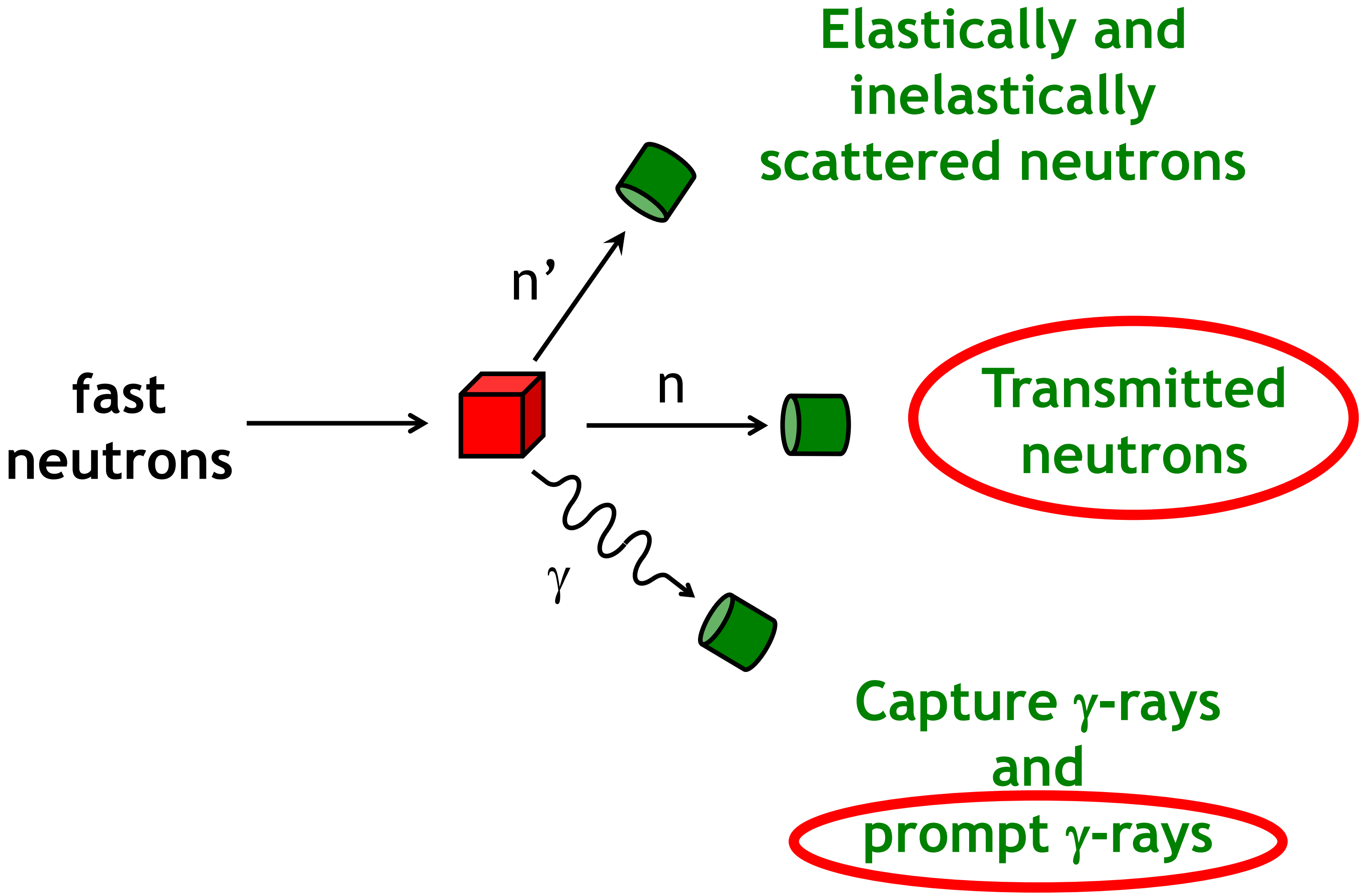


Elastically and inelastically scattered neutrons

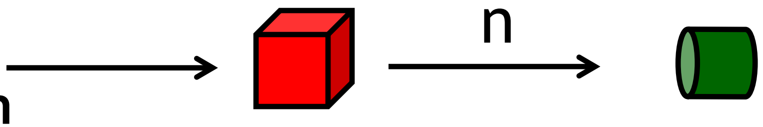
Transmitted neutrons

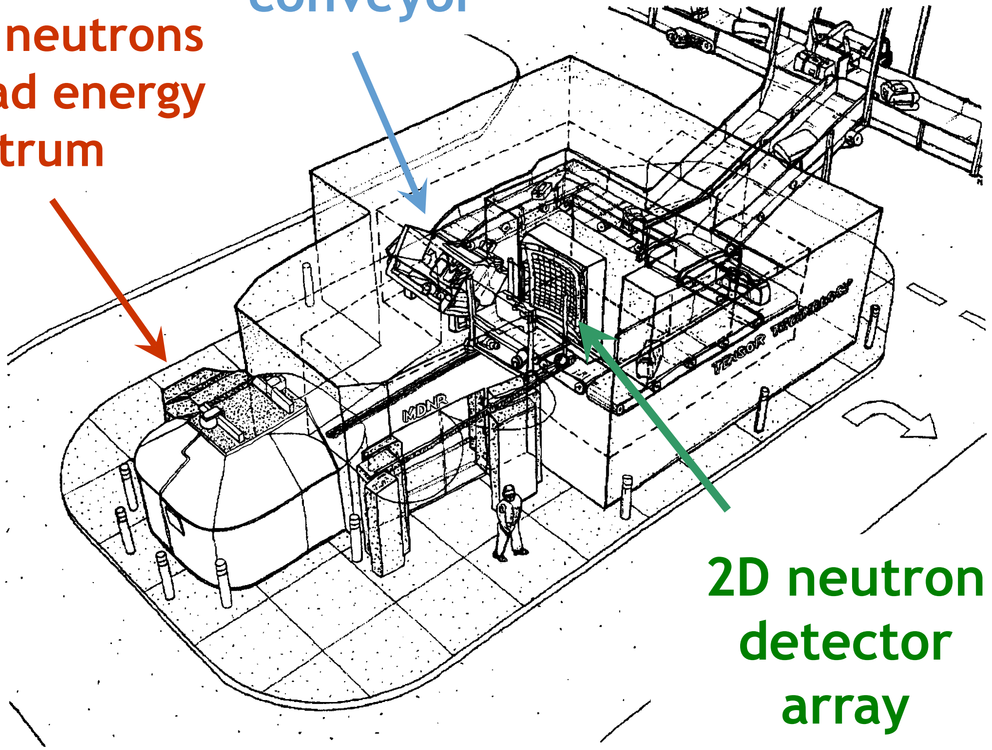
Capture γ-rays and prompt γ-rays

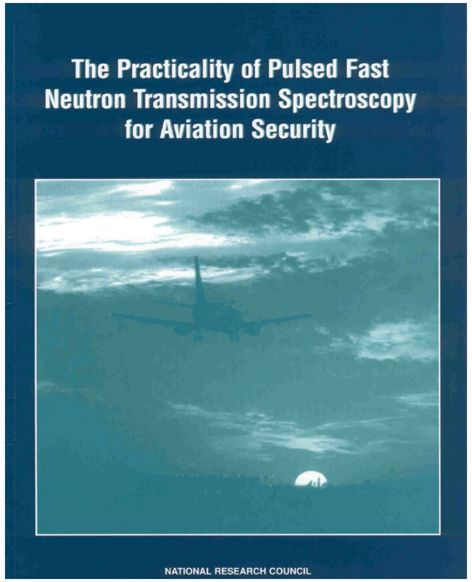
Fast neutron-based techniques for elemental characterization



Pulsed Fast Neutron Transmission Spectroscopy (Overley 1990)



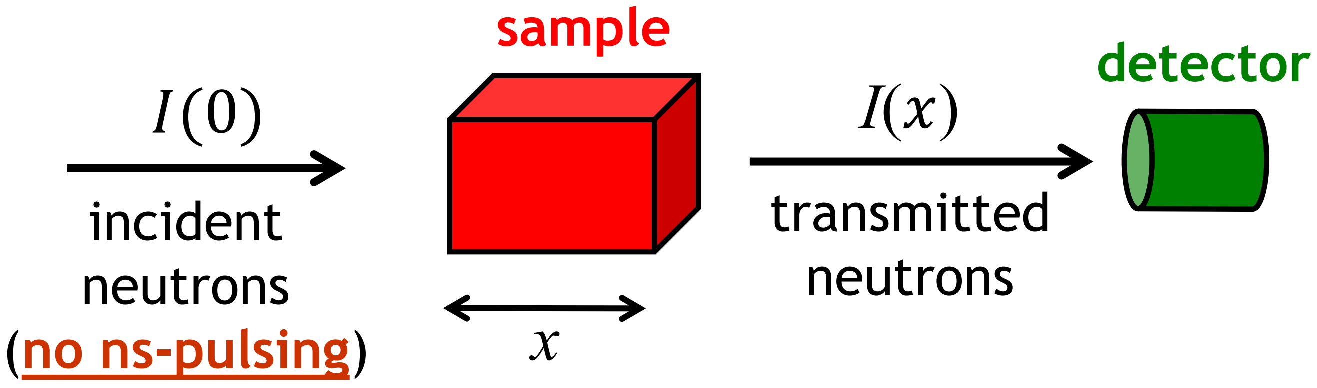




Panel on the assessment
of the practicality of
Pulse Fast Neutron Transmission
Spectroscopy for Aviation Safety

Report: 1999
Washington D.C.

Fast neutron transmission analysis (FNTA)

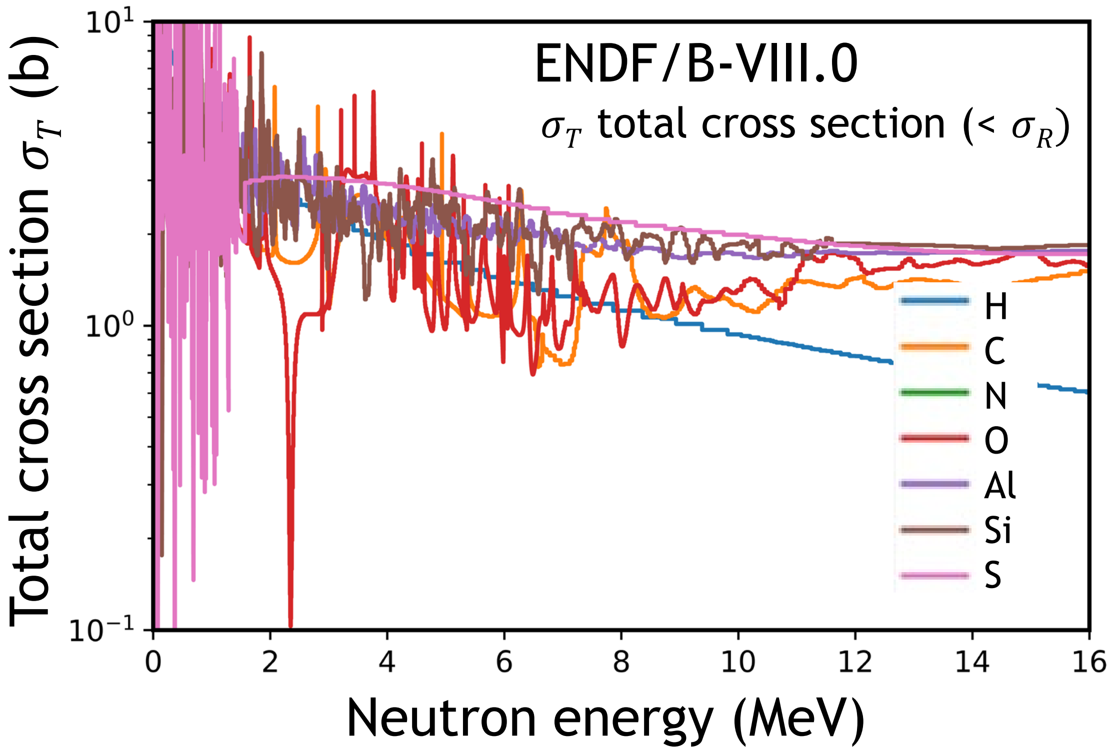


$$I(x) = I(0)\exp(-\Sigma_R x)$$

Σ_R : macroscopic removal cross section

$$\sigma_R = \Sigma_R / N_D$$

σ_R : microscopic removal cross section
N_D : nuclear number density



For multi-elemental samples:

$$\sigma_{R_{\text{sample}}} = \sum_{k=1}^{n} \boldsymbol{A_k} \sigma_{R_k}$$

$\boldsymbol{A_k}$: number of atoms of element k

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n lab

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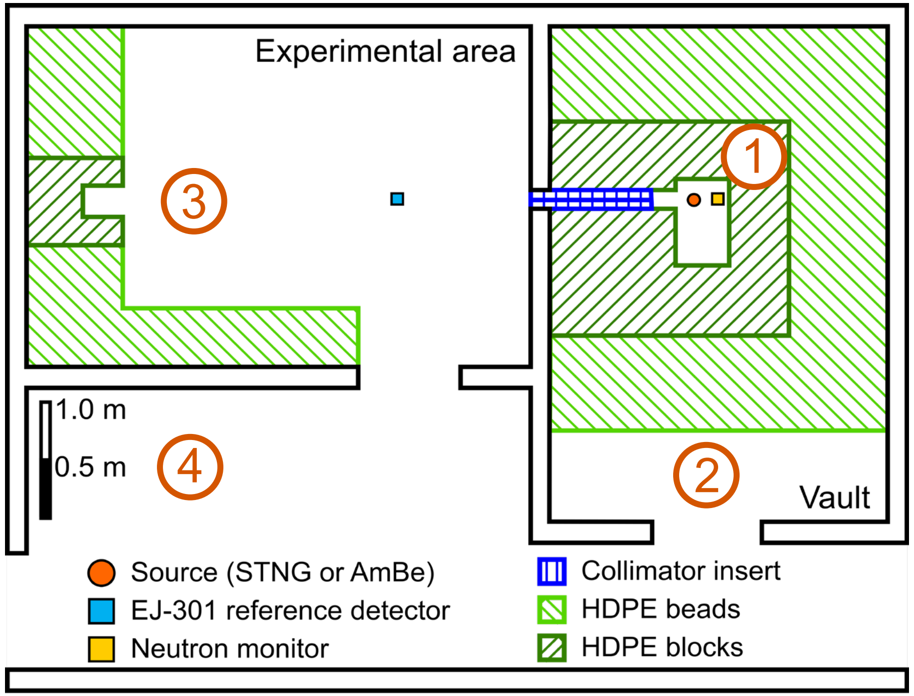

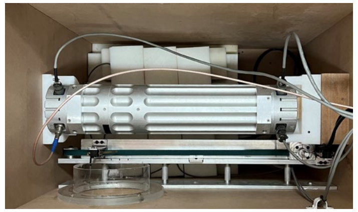

MP 320 sealed tube neutron generator

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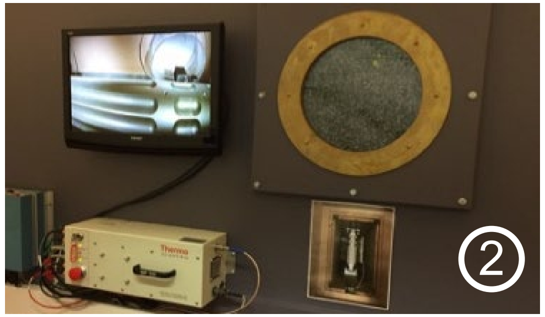
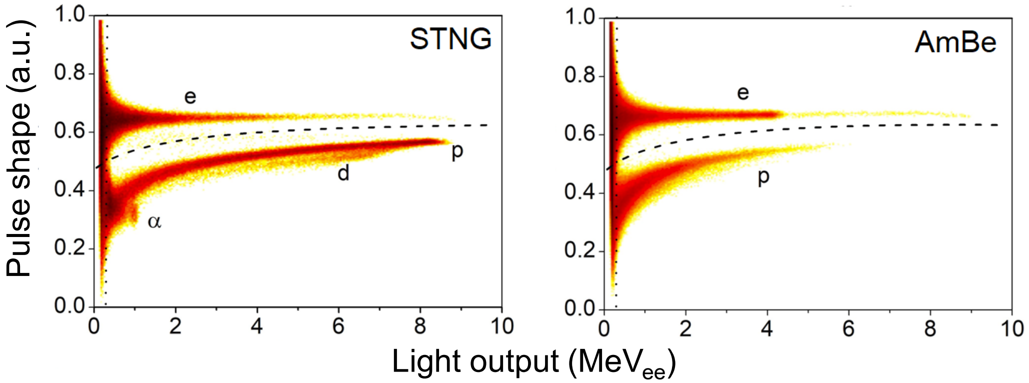
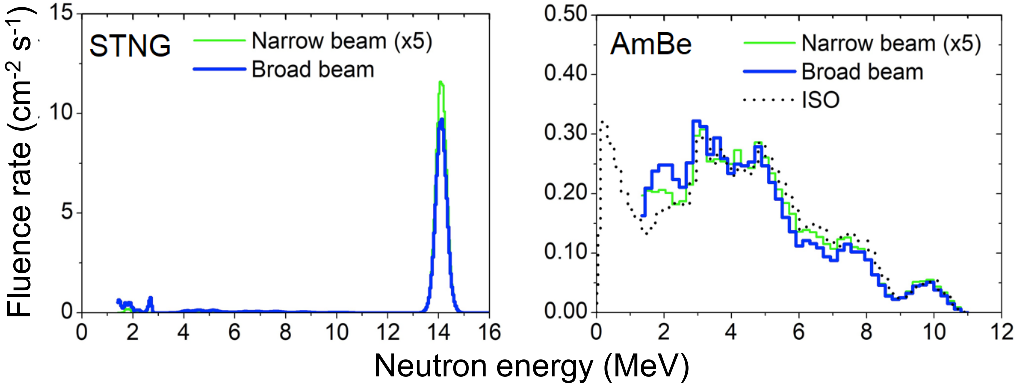
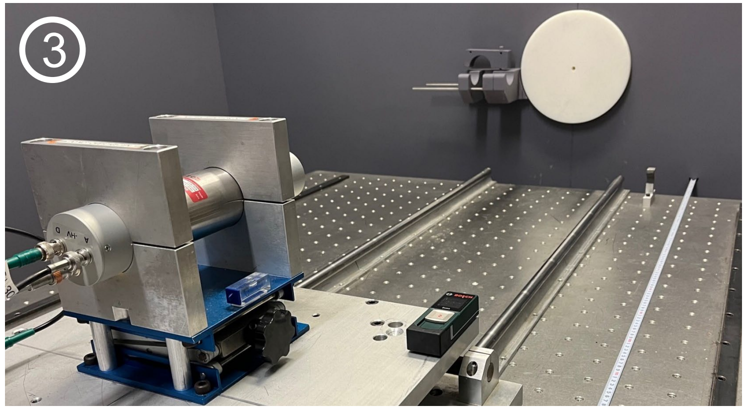
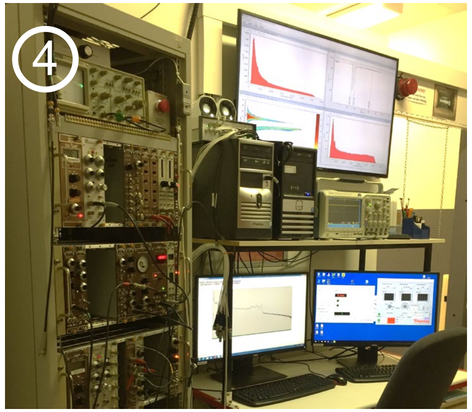
Americium-beryllium (220 GBq)







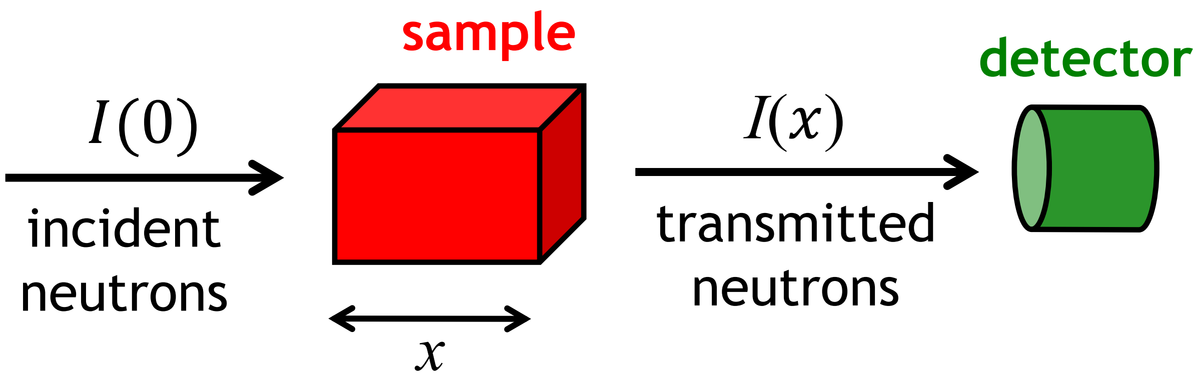




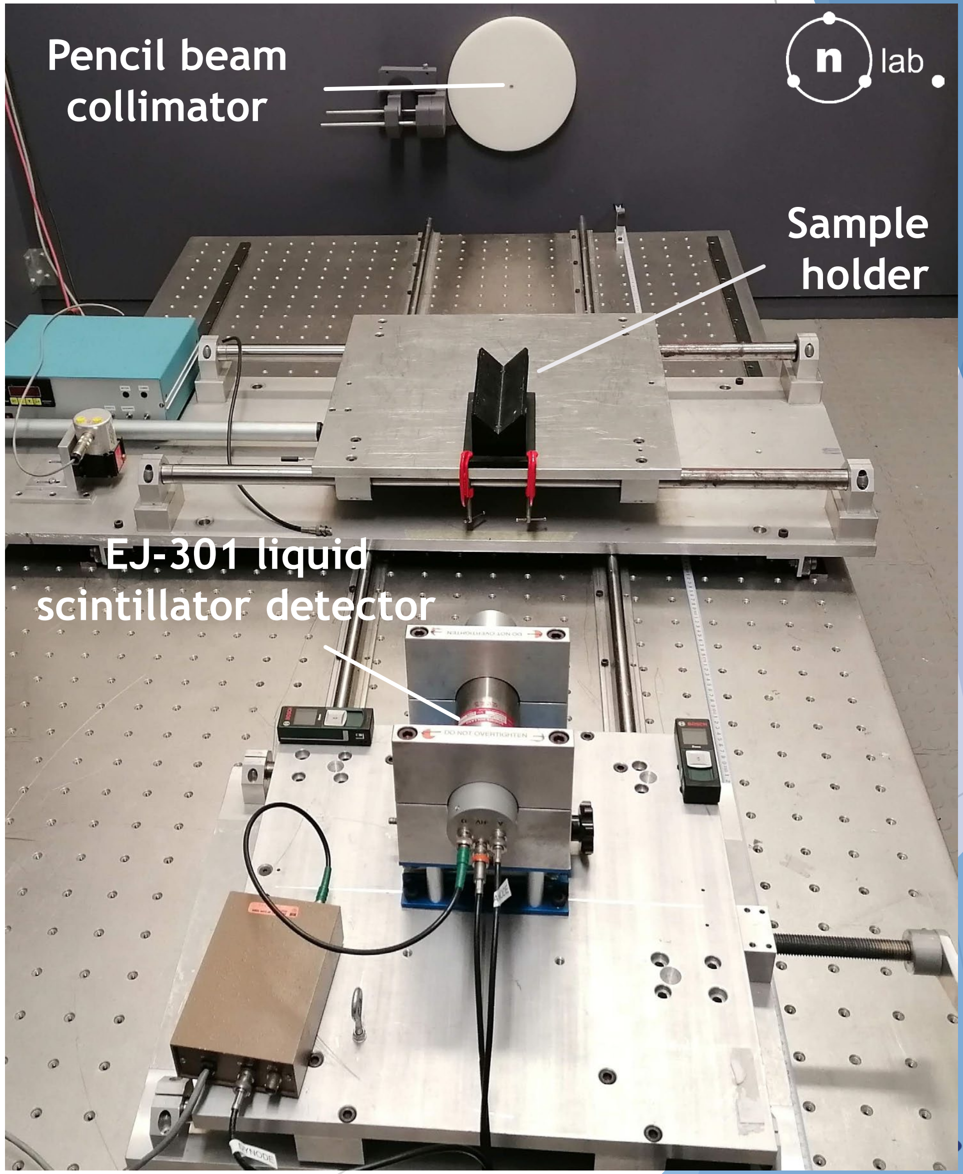
	STNG	AmBe
Reaction	$^{3}H(^{2}H, n)^{4}He$	$^{9}Be(\alpha, n)^{12}C + \gamma$ (4.4 MeV)
Neutron energy (MeV)	14.103(85)	thermal to ~11.0 MeV
Emission rate (s^{-1})	10^{8}	10^{7}
$\phi_{>1.5\ MeV}$ [narrow] (cm^{-2} s^{-1})	24.2(47)	1.350(84)
$\phi_{>1.5\ MeV}$ [broad] (cm^{-2} s^{-1})	102(12)	6.745(35)

Tanya Hutton & Andy Buffler, "Characterisation of neutron fields at the n-lab, a fast neutron facility at the University of Cape Town", *ARI* **206** (2024) 111196

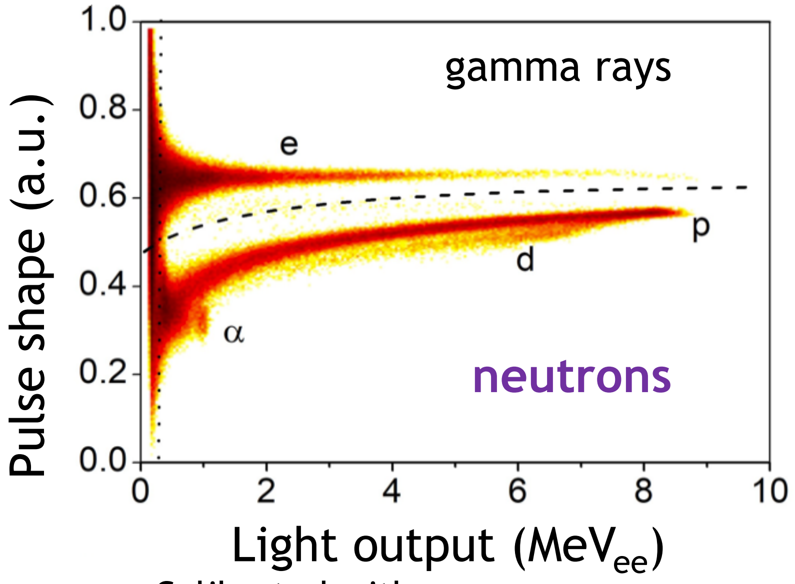
Fast neutron transmission analysis (FNTA): Experimental



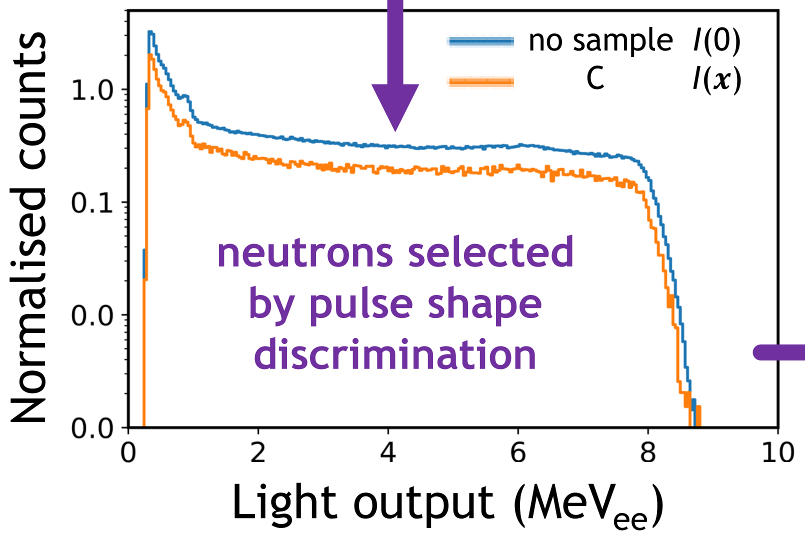
Standard samples prepared in Ø 6 cm x 10 cm cups



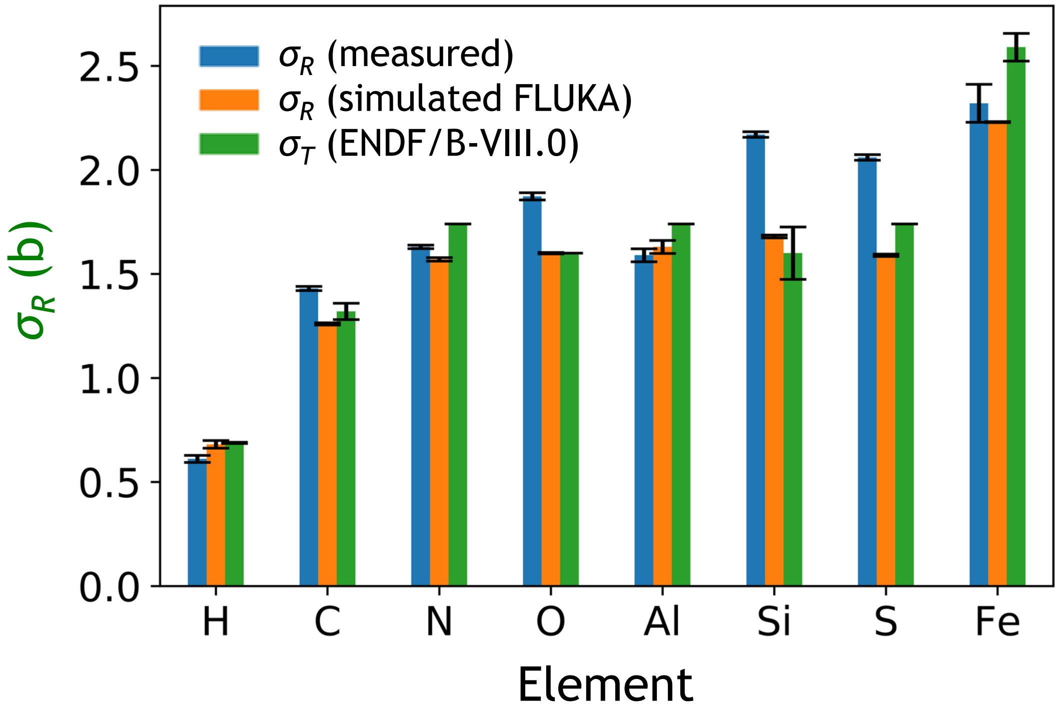
Fast neutron transmission analysis: STNG 14 MeV neutrons



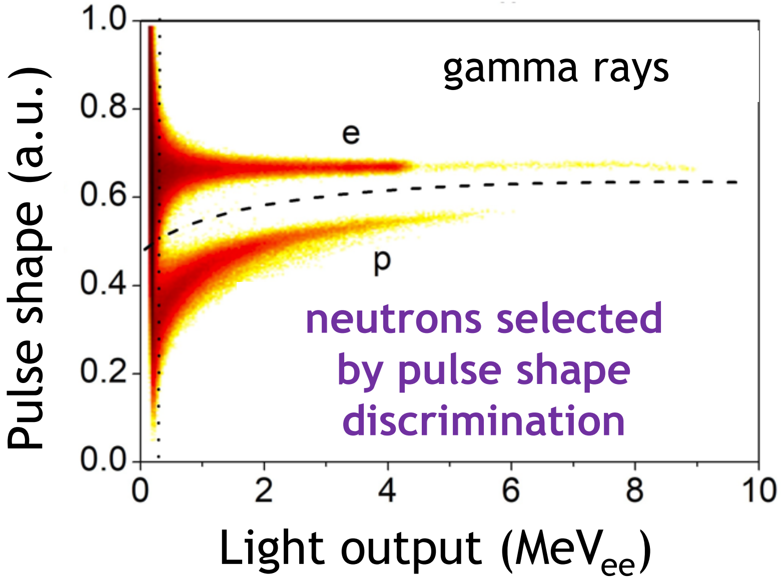
Calibrated with gamma ray sources



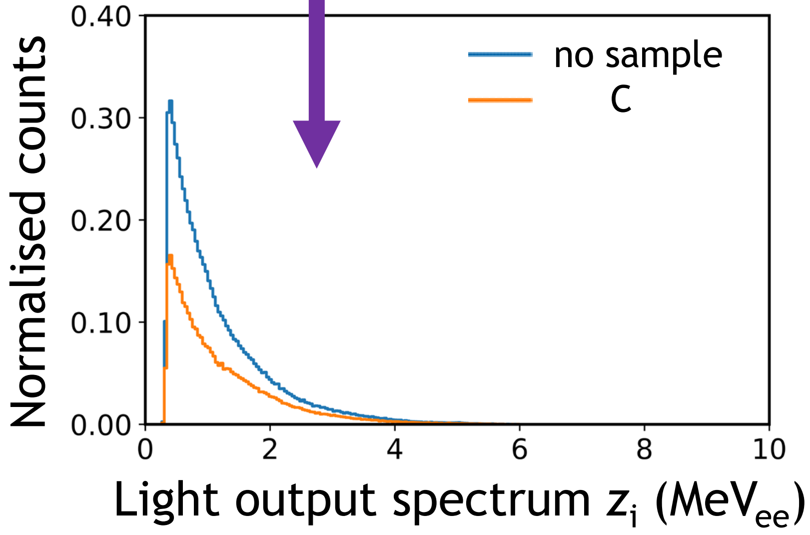
$$I(x) = I(0)\exp(N_D \sigma_R x)$$

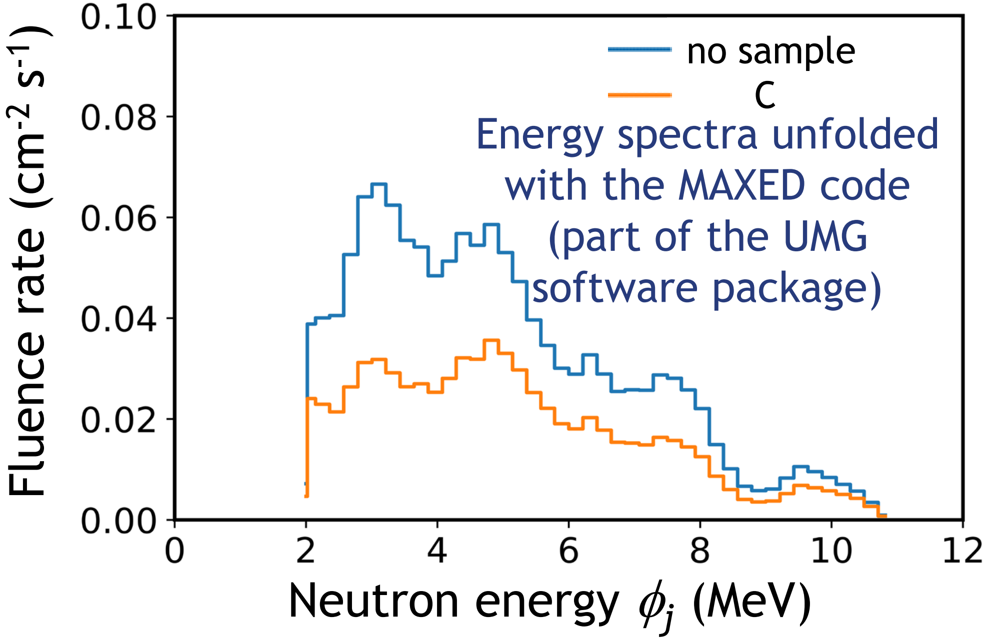


Fast neutron transmission analysis: AmBe neutrons

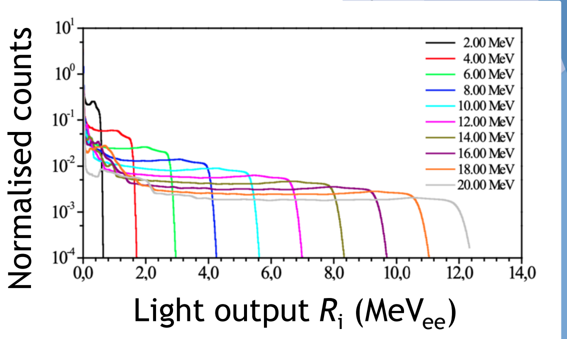


Calibrated with gamma ray sources





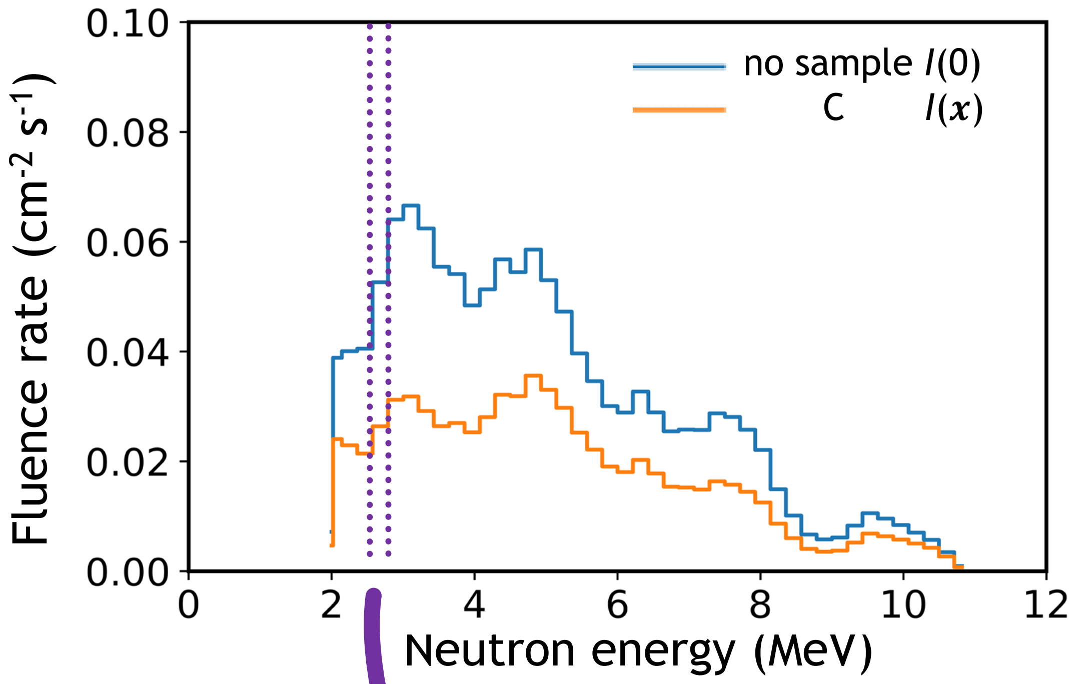
$$z_i = \sum_{j=1}^{m} R_{ij}\phi_j$$



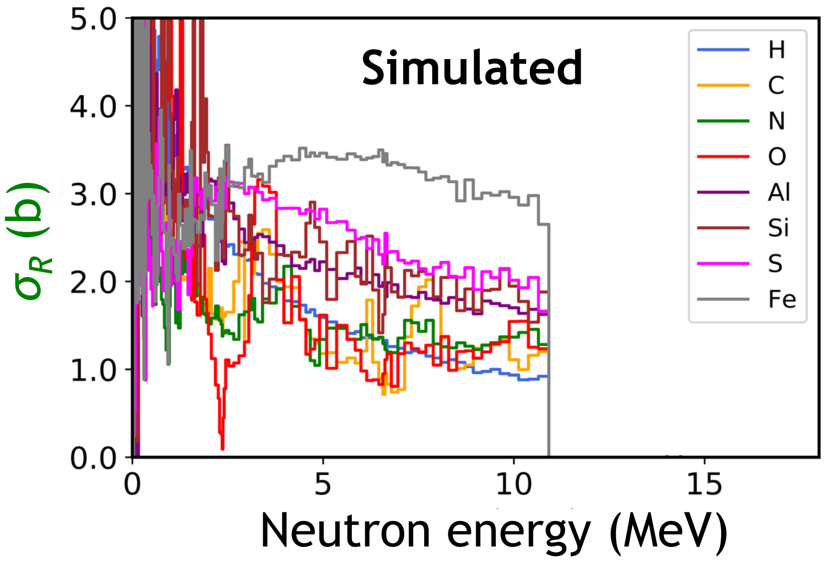
Neutron energy spectra ϕ_j obtained from unfolding analyses using known detector response functions R_{ij}.

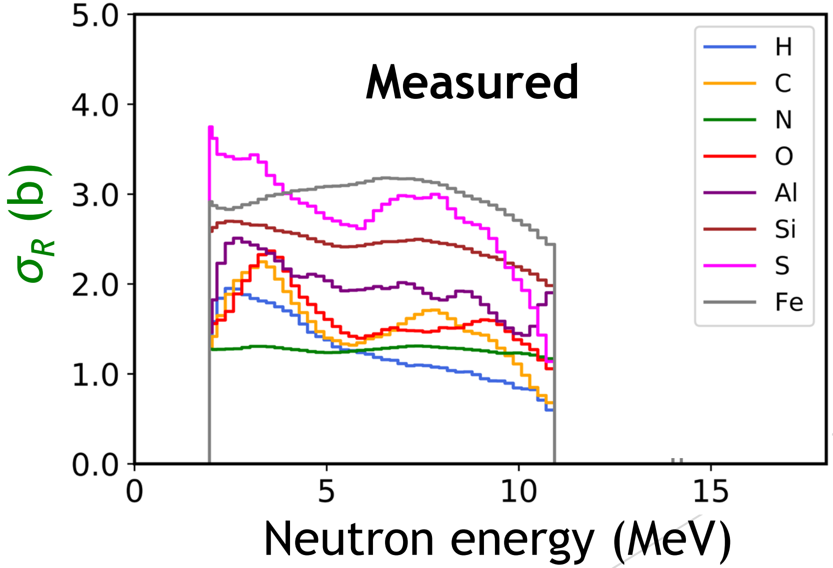
AccelApp'24 Norfolk, Virginia

Fast neutron transmission analysis: AmBe neutrons

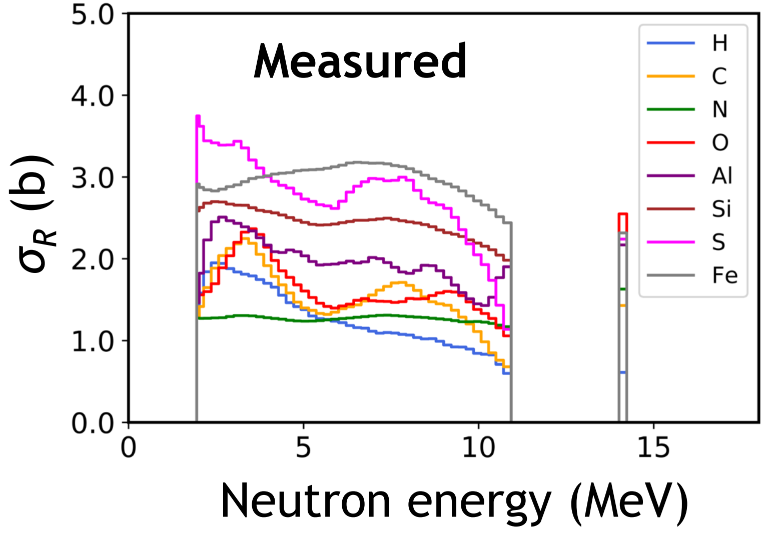


$$I(x) = I(0)\exp(N_D \sigma_R x)$$

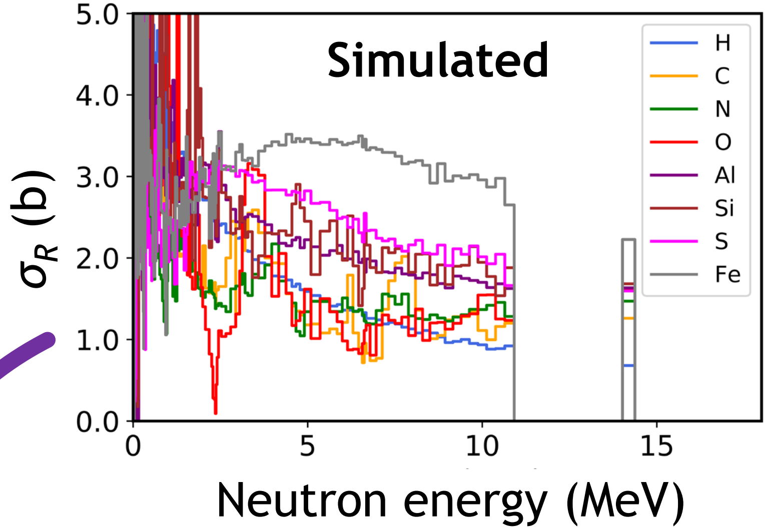




Examples of unfolding of elemental ratios with FNTA signatures

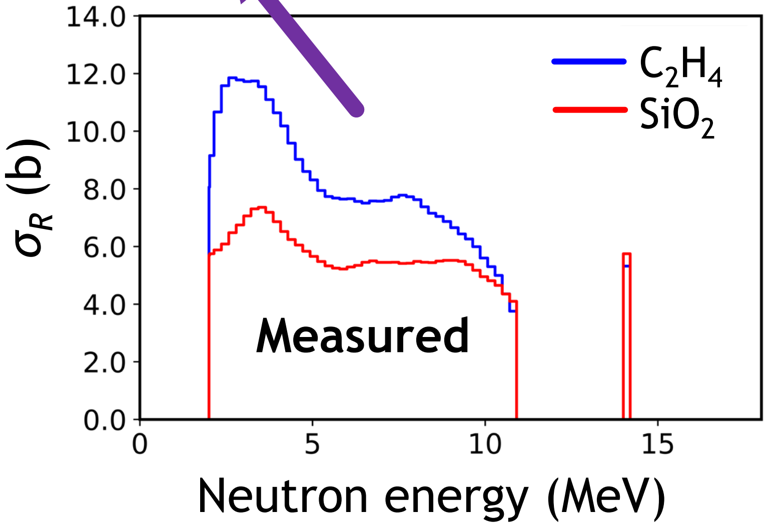


or

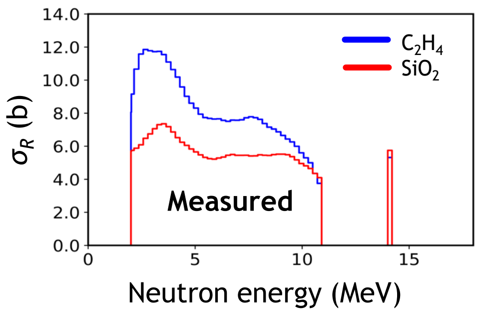


$$\sigma_{R_{\text{sample}}} = \sum^{n} A_k \sigma_{R_k}$$

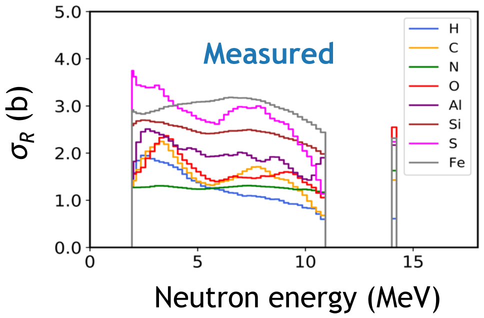
Deconvolve number of atoms *A* of element *k* through an iterative unfolding algorithm



Examples of unfolding of elemental ratios with FNTA signatures



$$\sigma_{R_{\text{sample}}} = \sum_{k=1}^{n} A_k \sigma_{R_k}$$



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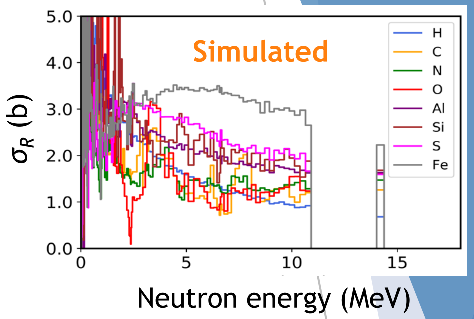

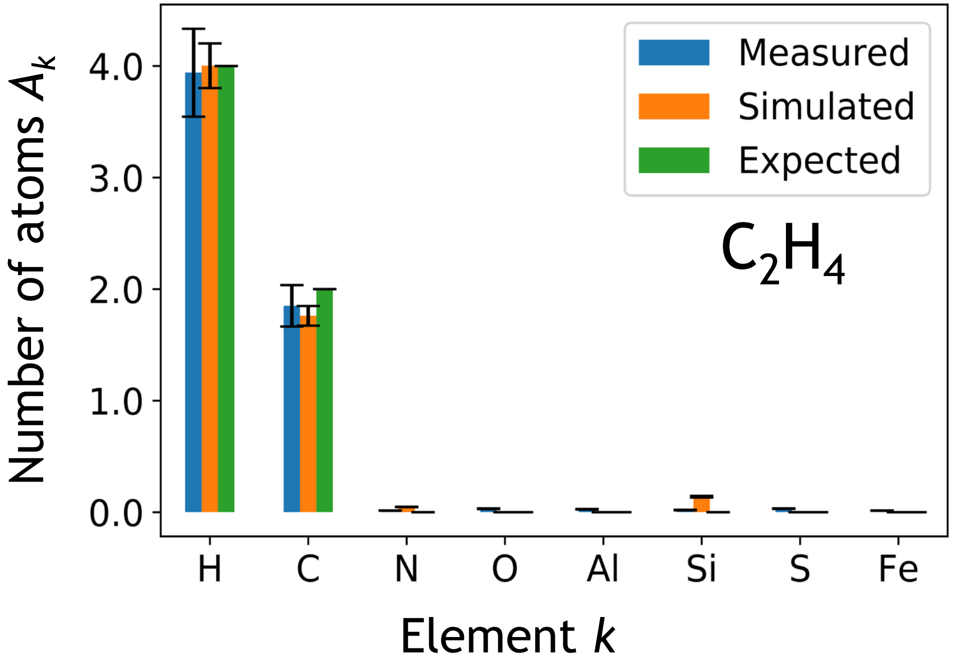

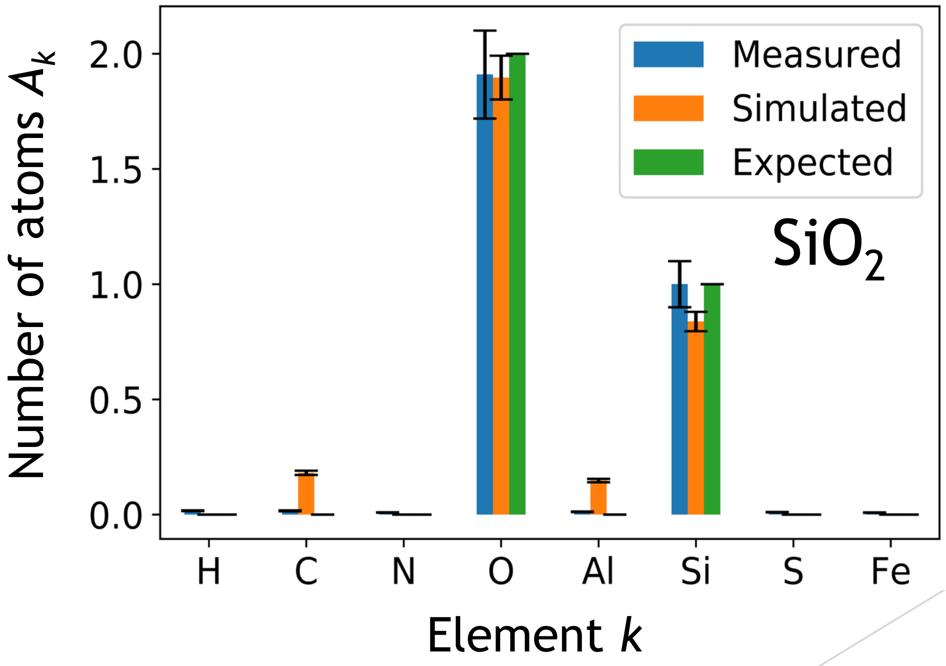

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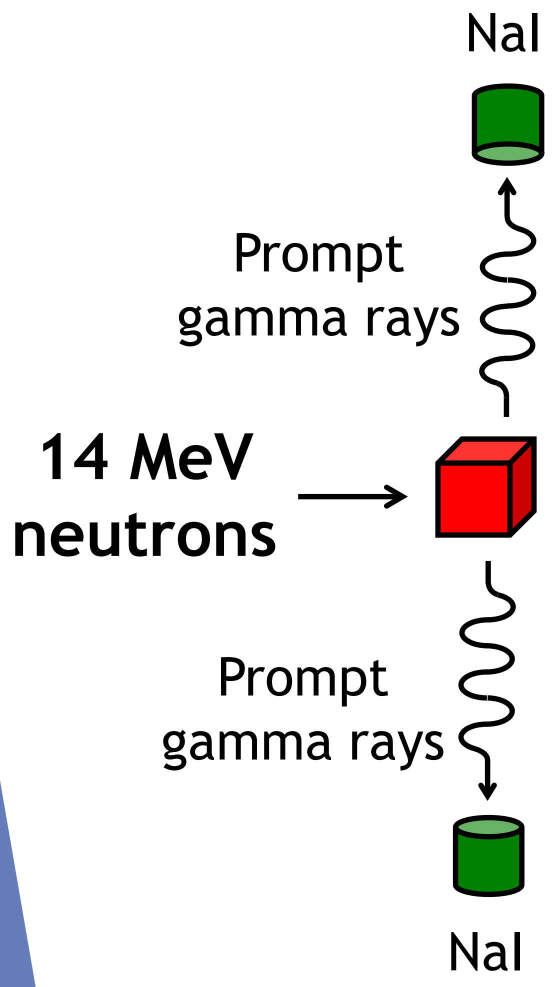
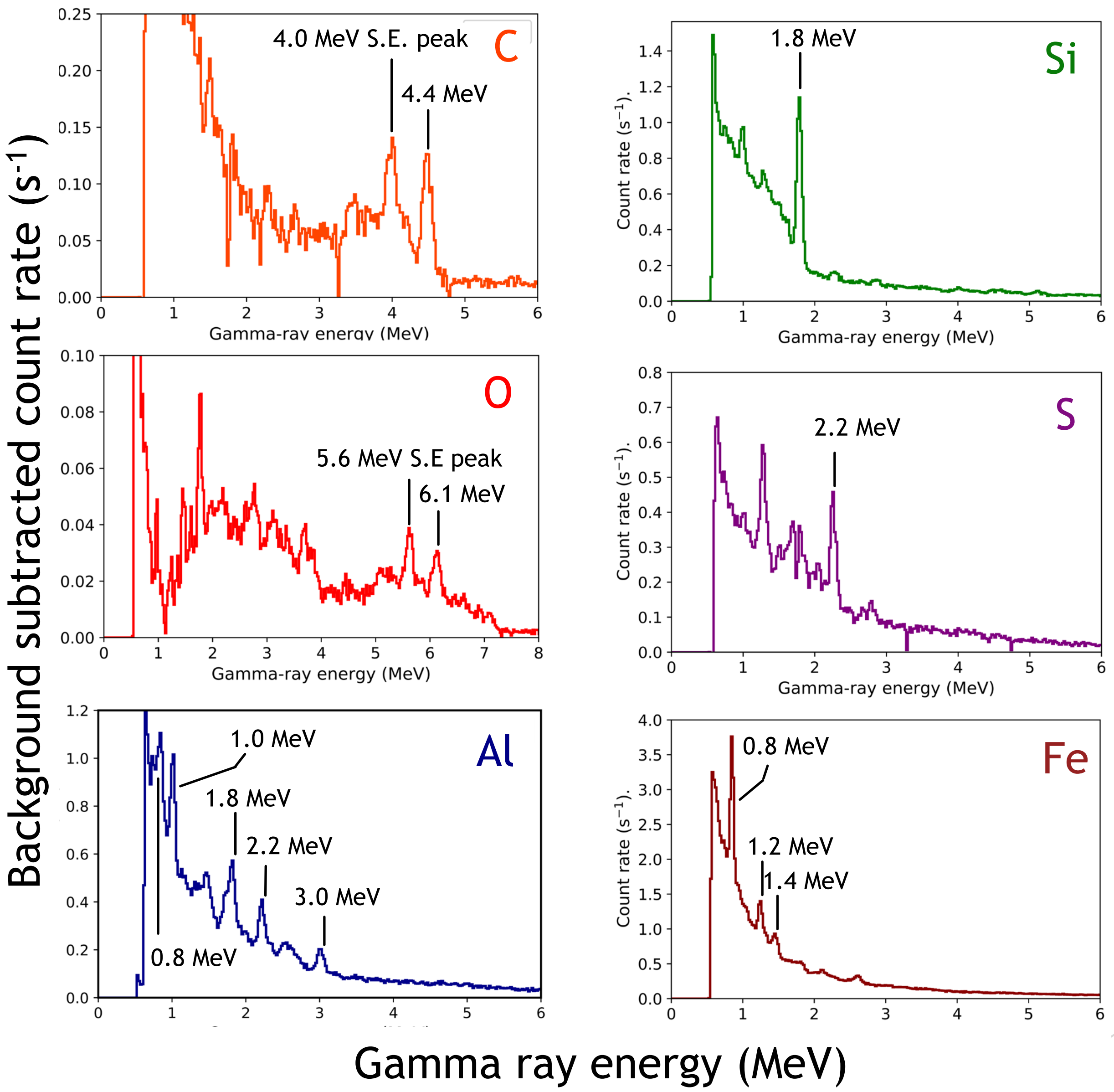
Prompt gamma analysis (PGA) to augment FNTA

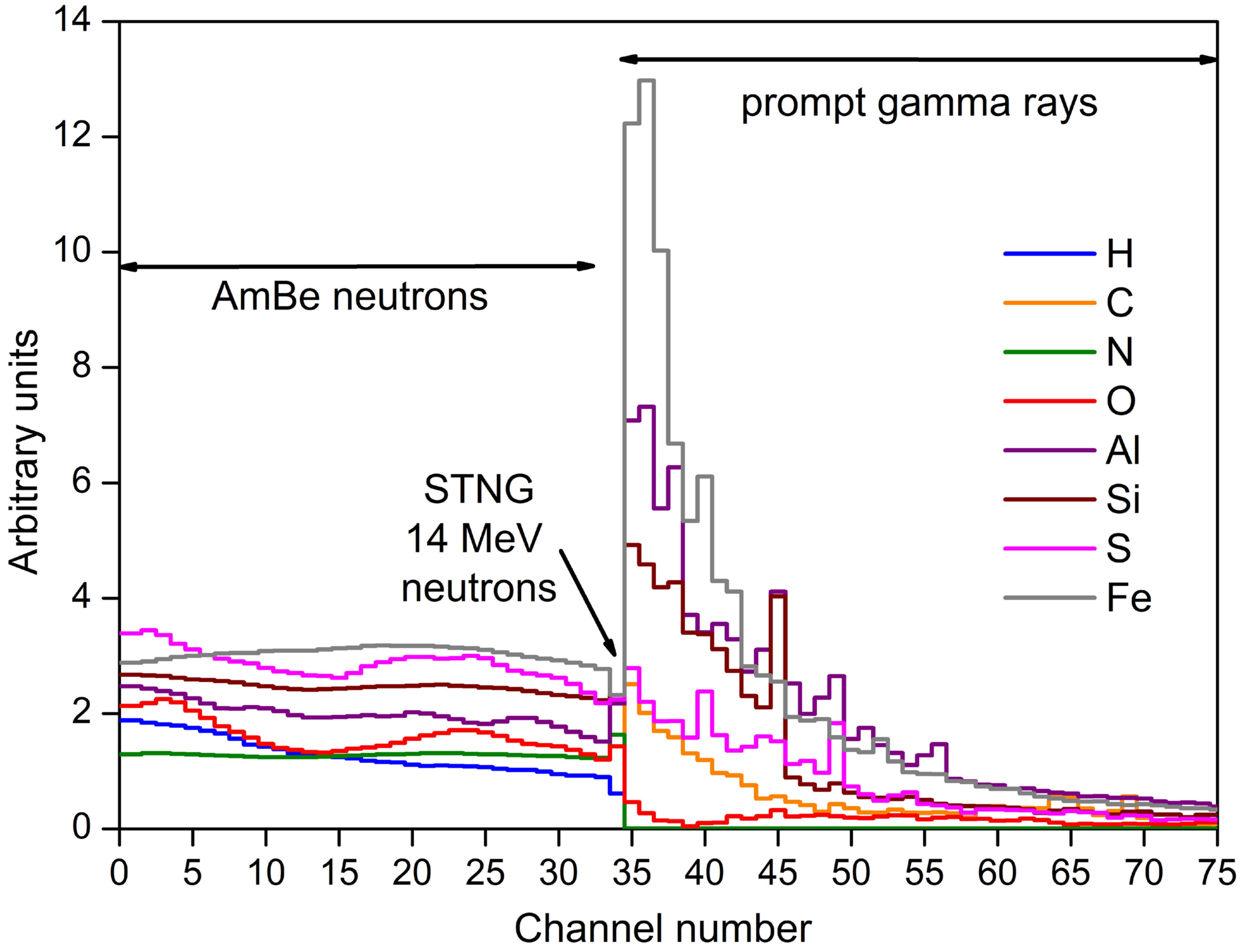




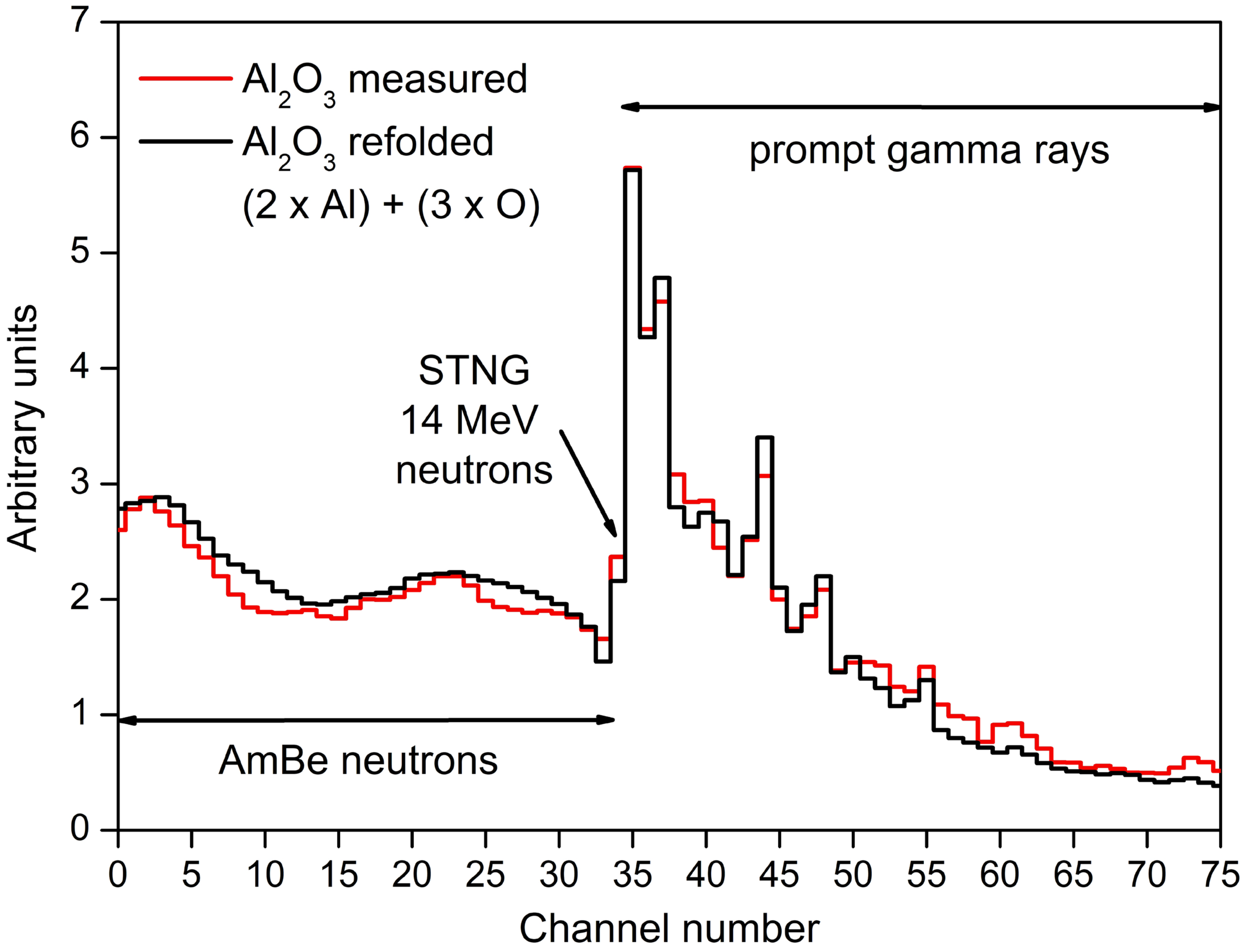
Gamma ray energies from (n,n’γ)

Element	E_γ (MeV)
C	4.4
O	6.1
Al	0.8, 1.0, 1.8, 2.2, 3.0
Si	1.8
S	2.2
Fe	0.8, 1.2, 1.4

Multimodal (neutron and gamma ray) elemental "signatures"



Example: reconstruction of Al_2O_3



Summary and present work

- Transmitted neutron signatures of all elements of interest have been measured and simulated for neutrons produced by a D-T sealed tube neutron generator and ^{241}Am-Be source.

- Number of atoms of each element in multi-elemental samples were determined using an iterative unfolding algorithm within 10%.

- Prompt gamma ray signatures measured for each element are distinctive and enhance the sensitivity of the multimodal technique when combined with neutron transmission analyses.

- The addition of transmitted gamma ray signatures is being explored to improve distinction between high mass elements.

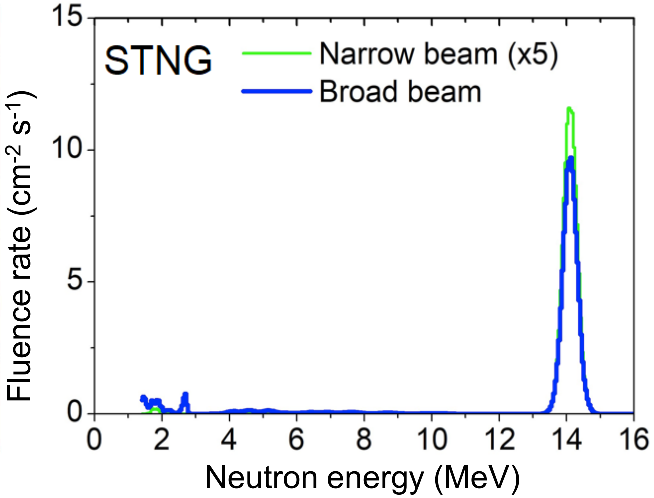
Thank you

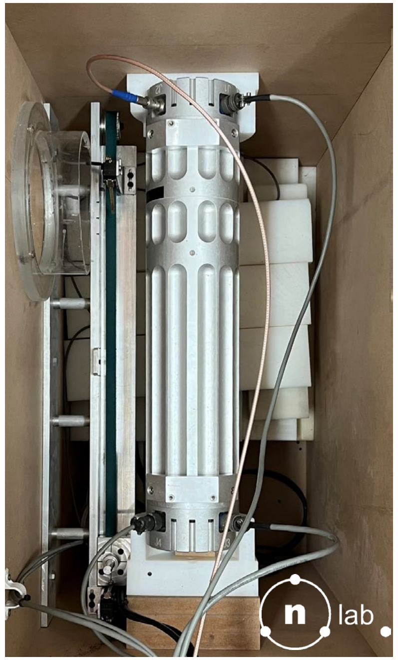
Questions are welcome

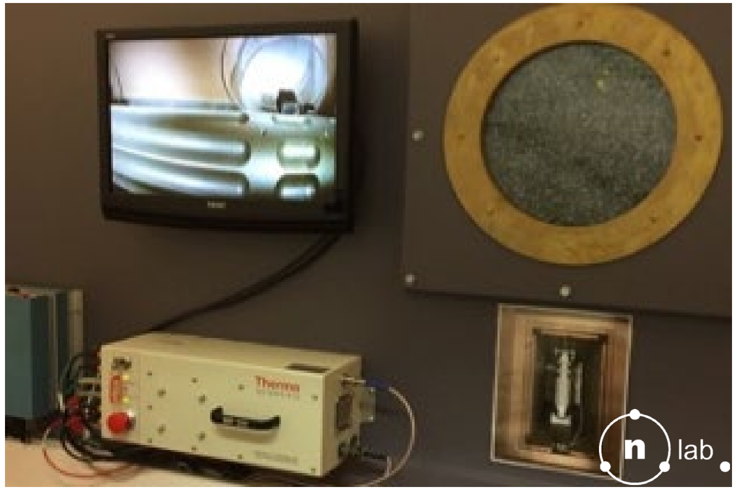
The authors wish to thank the AccelApp'24 conference organisers,
University Research Committee and Department of Physics, University of Cape Town,
and iThemba LABS for their financial support in attending this conference.

ThermoFisher SCIENTIFIC

MP 320 neutron generator







Parameter	Value
Neutron energy	14.1 MeV
Reaction	$^{3}H(^{2}H, n)^{4}He$ (^{3}H doped Zr target)
Maximum neutron yield	~10^{8} s^{-1}
Accelerator voltage	50 - 90 kV
Deuteron beam current	30 – 60 μA
Pulse rate	250 Hz – 20 kHz, or continuous
Minimum pulse width	5 μs
Duty cycle	5 – 100 %, 5 μs min. pulse width
Power requirement	< 50 W
Total mass	12 kg
Accelerator dimensions	12 cm (diameter) x 56 cm