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

Sizwe Mhlongo*, Andy Buffler, Tanya Hutton, Zina Ndabeni
Department of Physics, University of Cape Town, South Africa

Abstract

Developing methods to non-destructively determine the elemental composition of bulk materials is important in a broad range of contexts, including food and agriculture, coal and minerals processing, contraband detection, and nuclear regulation. A combination of two neutron-based techniques are being explored in this work: fast neutron transmission; and prompt gamma ray analysis. Characteristic radiation signatures were measured, and simulated, for a series of elements relevant to the context of coal quality assurance using collimated fast neutron beams at the n-lab, a fast neutron facility within the Department of Physics, University of Cape Town. These radiation signatures were used to form a library of elemental responses, which were then used to deconvolve mass ratios of elements through an iterative unfolding algorithm.

Motivation

- **Coal** plays a central role in the electrical power production in South Africa and other developing countries.
- Knowledge of elemental composition has economic and environmental consequences.
- Existing techniques are largely destructive, and have limited sensitivity to hydrogen e.g. x-ray diffraction

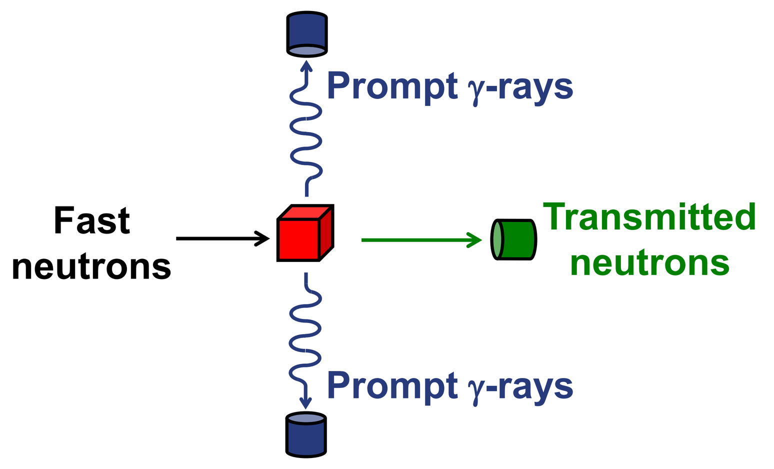
Element	% by mass
Carbon	77-80
Hydrogen	4-5
Oxygen	12-15
Nitrogen	2-3
Sulphur	1-2
Ash (SiO_2, Al_2O_3, Fe_2O_3, …)	

Typical coal composition [1]

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.

Concept

- Fast neutrons are highly-penetrating and produce radiation signatures that are characteristic of sample composition.
- Different fast neutron-based techniques show different sensitivities to different elements, so the combination of two or more methods will broaden the range of detectable elements.



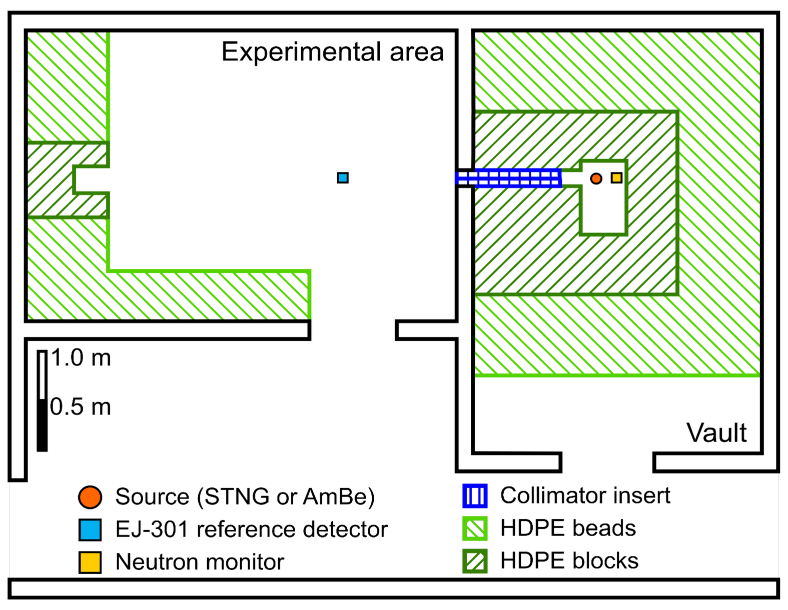
Radiation signatures investigated here are from **transmitted neutron** spectra and **prompt gamma ray** emissions from inelastic scatter.

Measurements at the n lab

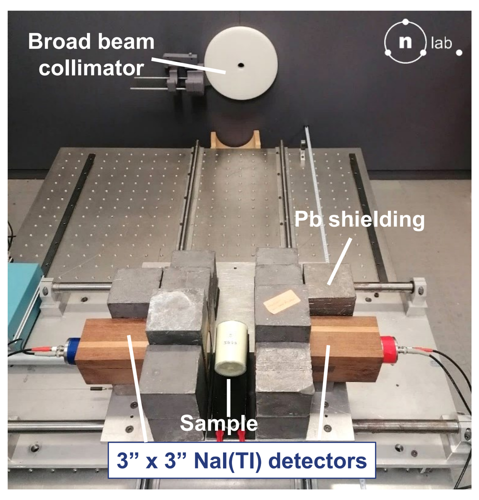
Neutron sources:
- D-T sealed tube neutron generator; 14.1 MeV
- 220 GBq ^{241}Am-Be; thermal - 11 MeV

Samples:
- Elemental: C, N, Al, Si, S, Fe
- Mixtures: SiO_2, $(C_2H_4)_n$, Al_2O_3

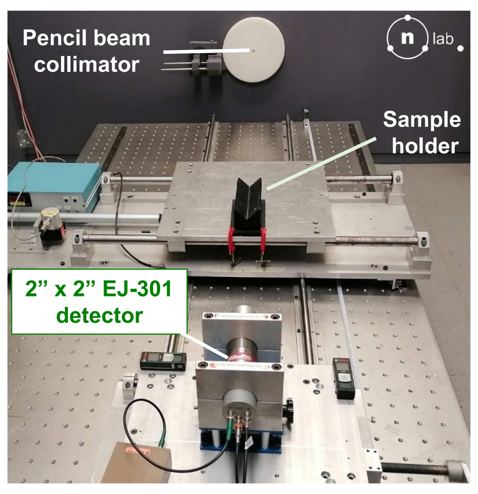
Samples in Ø 6 cm x 10 cm containers.



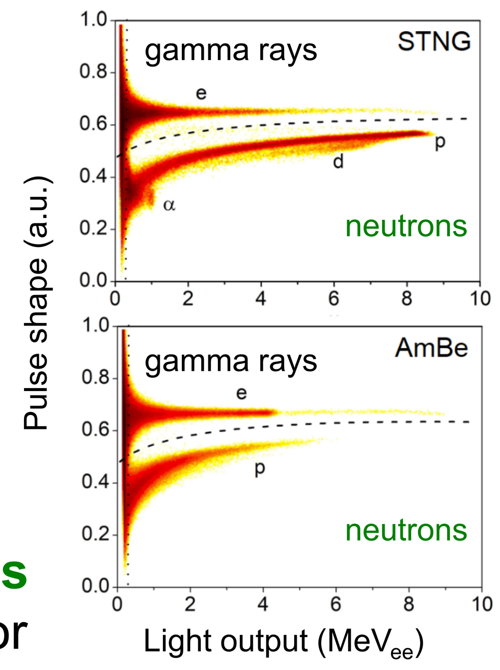
Layout of the n-lab [2].



Prompt gamma rays
two 3" x 3" NaI(Tl) detectors



Transmitted neutrons
2" x 2" EJ-301 detector

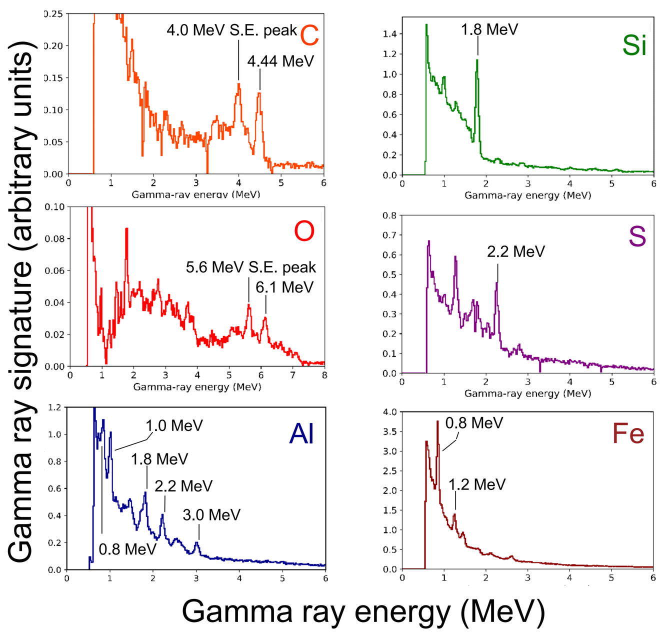


Prompt gamma ray analysis

Gamma rays from inelastic scatter (n, n'γ) measured and background subtracted.

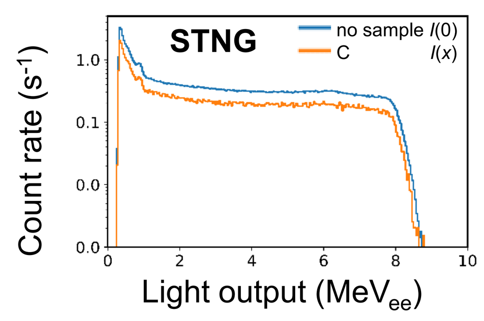
Normalised by number density N_D of sample.

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



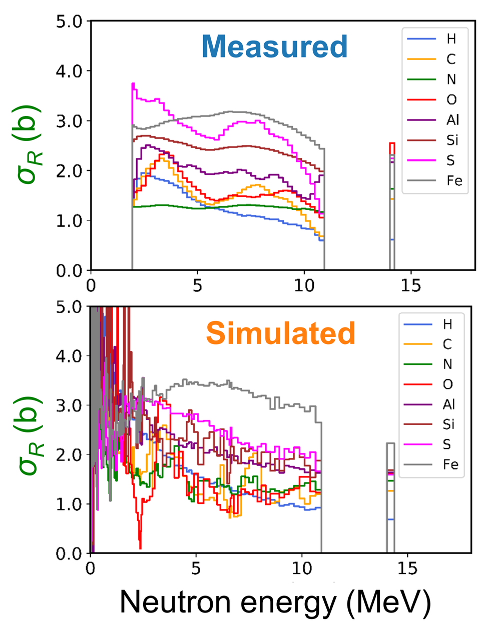
Fast neutron transmission analysis

Neutron events in EJ-301 selected by pulse shape discrimination.

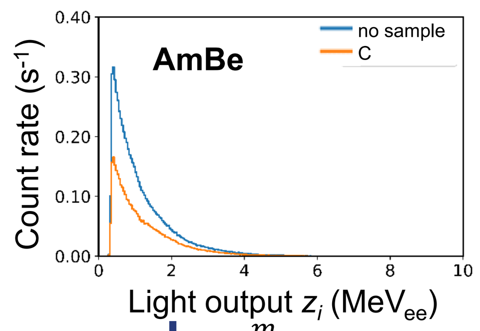


$$I(x) = I(0)\exp(-N_D \sigma_R x)$$

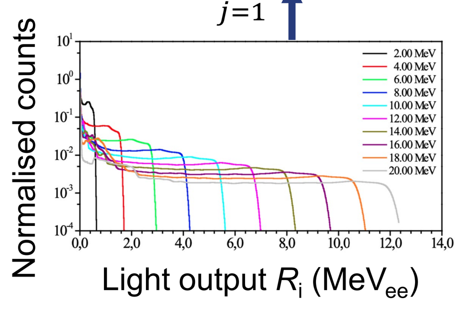
σ_R : microscopic removal cross section
N_D : nuclear number density

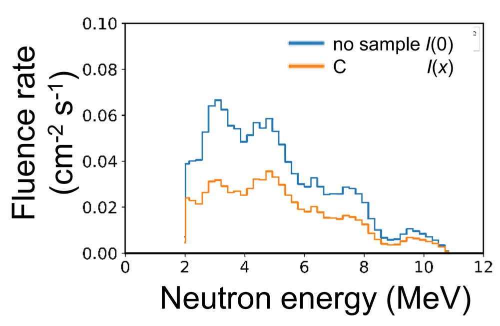


For ^{241}Am-Be, neutron fluence spectrum ϕ_j obtained from unfolding analyses using known detector response functions R_{ij}.



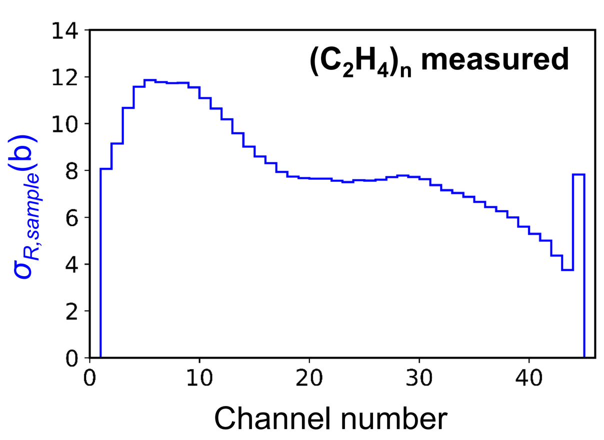
$$z_i = \sum_{j=1}^{m} R_{ij}\phi_j$$

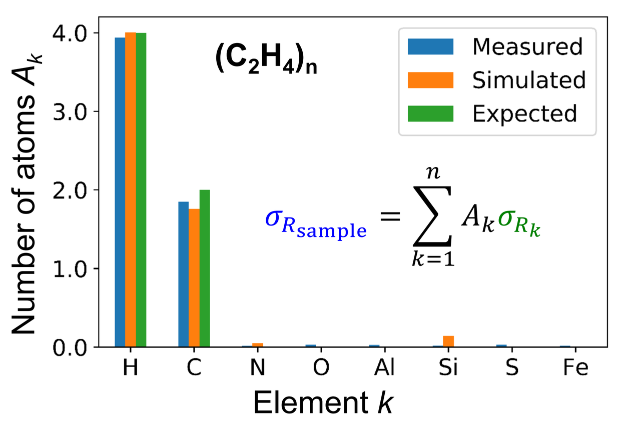




Elemental analysis

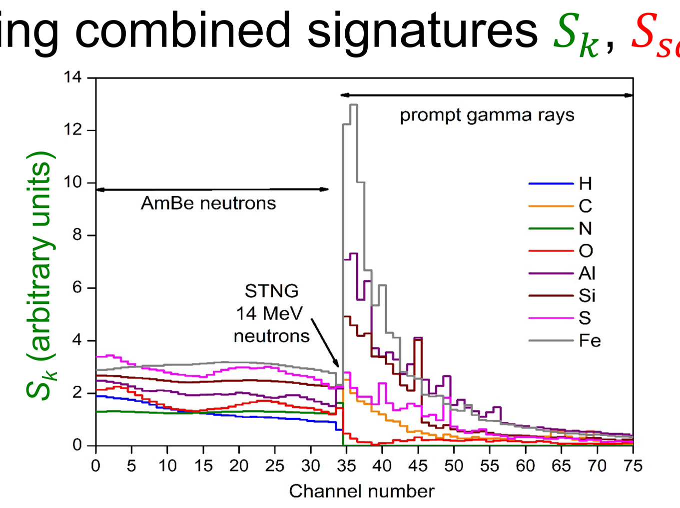
Elemental composition unfolded using measured and simulated transmission data for mixed samples.

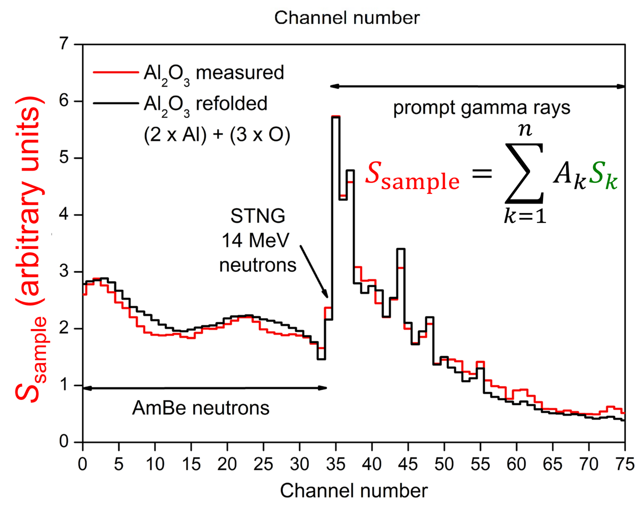




$$\sigma_{R_{sample}} = \sum_{k=1}^{n} A_k \sigma_{R_k}$$

Elemental composition reconstructed using combined signatures S_k, S_{sample}.





$$S_{sample} = \sum_{k=1}^{n} A_k S_k$$

Summary

- Elemental transmitted signatures measured and simulated for neutrons produced by a D-T sealed tube neutron generator and ^{241}Am-Be source.
- Elemental composition of multi-elemental samples were determined using an iterative unfolding algorithm within 10%.
- Addition of prompt gamma ray signatures will enhance distinction between elements.

References

[1] Matjie, R.H., et al. (2016) *Determination of mineral matter and elemental composition of individual macerals in coals from Highveld mines*, J. S. Afr. Inst. Min. Metall., 116:2
[2] Hutton, T., Buffler, A. (2024) *Characterisation of neutron fields at the n-lab, a fast neutron facility at the University of Cape Town*, Appl. Rad. Iso, 206 111196

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*mhlsiz016@myuct.ac.za