Monte Carlo N-Particle simulations of SABAT underwater chemical threats detection system using neutron activation analysis

Paweł Sibczyński (*Electronics and Detection Systems Division (TJ2), NCBJ*)

Michał Silarski, Vahagn Ivanian, Ewelina Kubicz, Szymon Niedźwiecki, Paweł Moskal, Juhi Raj, Sushil Sharma (*Jagiellonian University, Kraków*)

Oleh Trofimiuk (*Taras Shevchenko National University of Kyiv, Ukraine*)

SABAT
Stoichiometry Analysis By Activation Techniques

NARODOWE
CENTRUM
BADAŃ
JĄDROWYCH
ŚWIERK

A kind of foreword – my professional skills

- Expertise in radiation detection:
  - Scintillation detectors characterization and applciation
  - Photodetectors testing
  - Neutron detection (including digital PSD)
- MCNP simulations in any kind of application – Homeland Security, industry, nuclear medicine, fundamental physics
- Python programming and data analysis automation
- Projects management (currently C-BORD)
- Currently 43 publication published

What can we do with MCNP?

Design a device model

Evolve the device model

Gamma spectra reconstruction

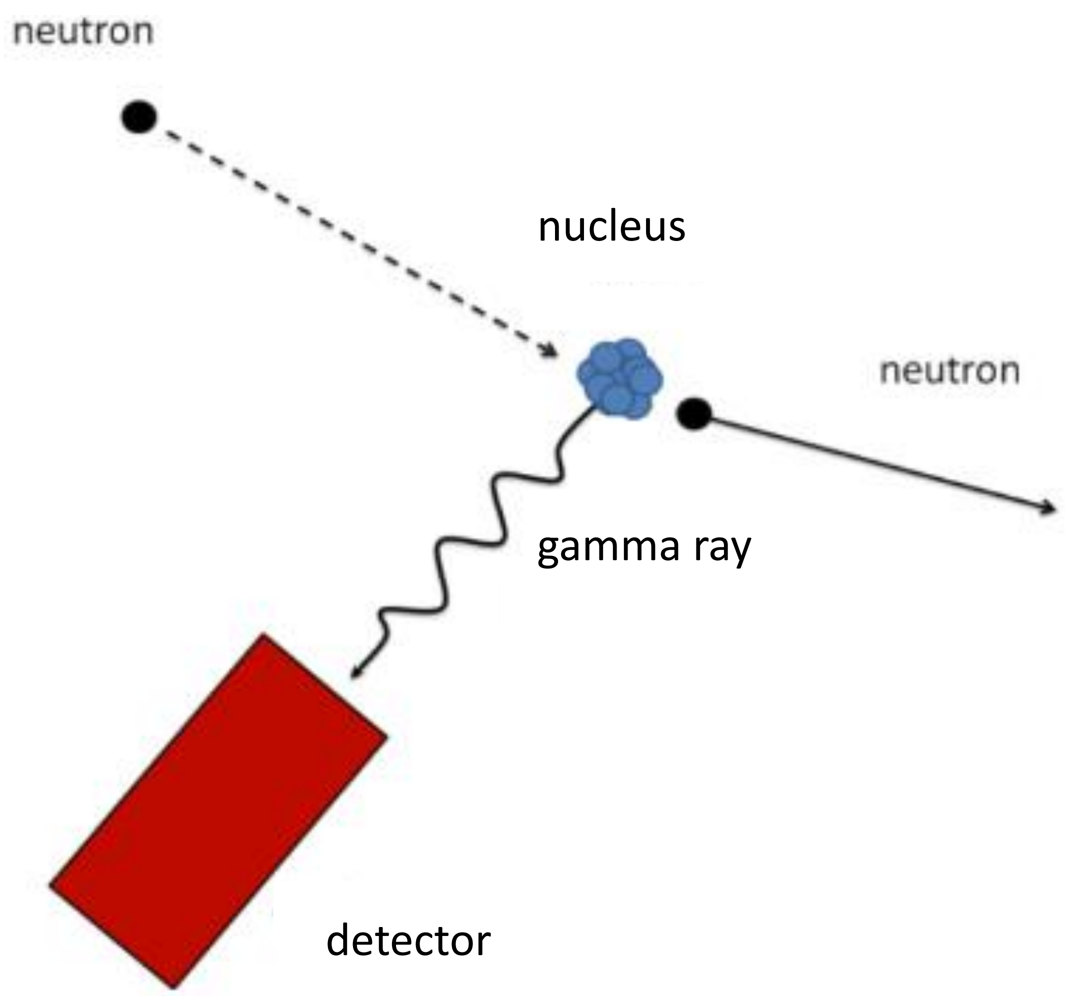
Particle tracking

Radiation fluence through

Surface

Cell

Neutron activation principle



How to do the MCNP simulations in SABAT?

Purchase license ☺

Write a not-user-frendly code

Use high performance computer or computing cluster. Final SABAT model performance was simulated on CIŚ NCBJ computing cluster with up to 3000 cores/user

Calculate pulse height tally

For delayed gamma rays – calculate average gamma flux in detector and pulse height tally

SABAT rationale

Environmental protection of sea areas

Over 250 kilotons of munition were sunk into Baltic Sea, mostly explosives, but also many chemical agents after 2nd World War.

It was estimated that if only 16 % of the sunk munition was released into the Baltic the life in the sea and at its shores would be entirely ruined for the next 100 years

How can we detect threat underwater with SABAT?

Dive the system underwater first

Activate the inspected object with neutrons – 14 MeV would be OK

Detect prompt gamma rays	Detect delayed gamma rays

Measure gamma peaks stoichiometry

Cl, S, C to O	Cl to H

Make decision – raise alarm or not

Substantiation of the choices – SABAT detection system

Neutron source

- D-T neutron generator (NG). 14 MeV neutrons have longer range in hydrogenuous environment and activate C and O by inelastic scattering

Detector

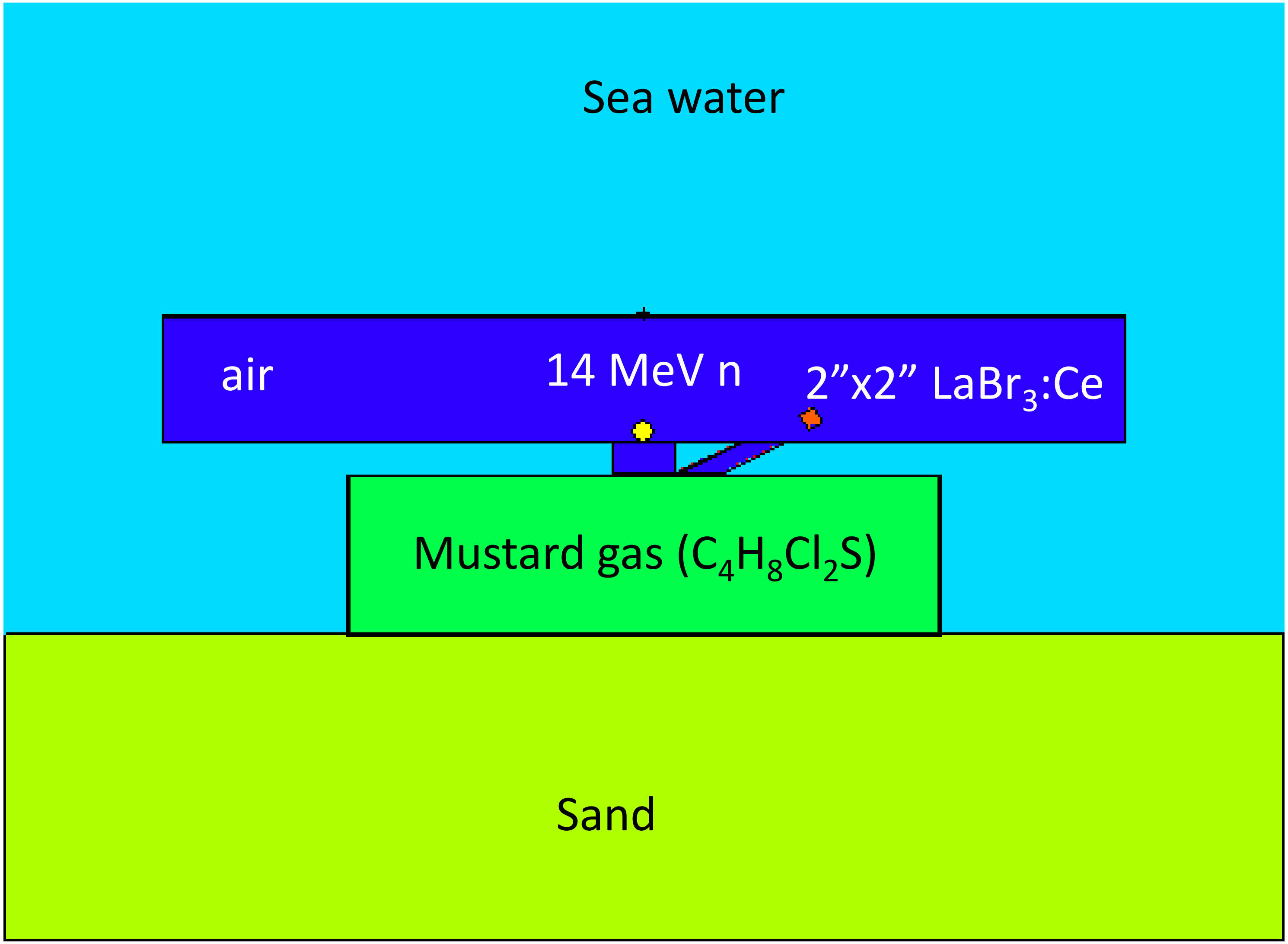
- $LaBr_3$:Ce (Brillance 380). Reasons?
- Excellent energy resolution (2.8% at 662 keV) [1,2]
- high light yield (>70000 ph/MeV) [1,2]
- short decay time of 18 ns [1]

Radiation guides

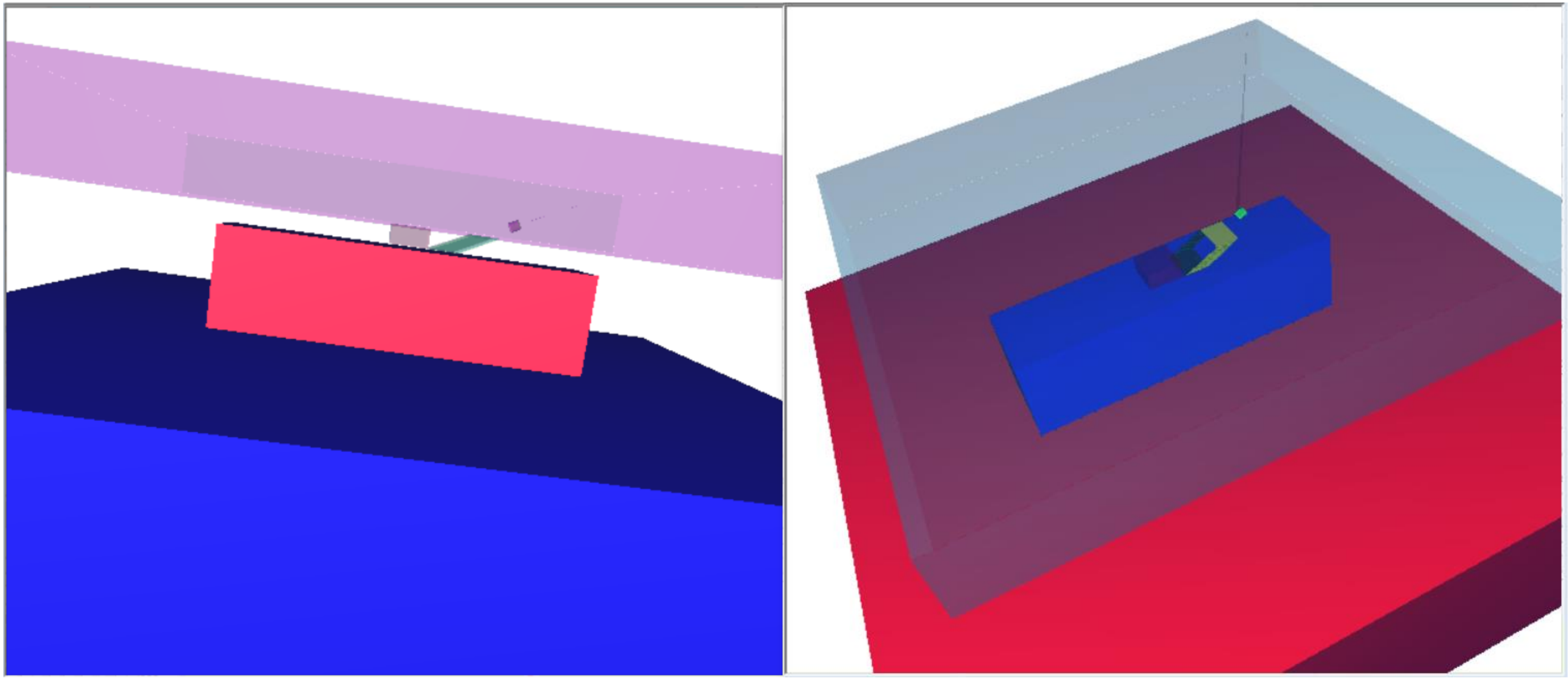
- Increase of neutrons and gamma rays range in water.

[1] E. van Loef et al. , Appl. Phys. Lett., Vol. 79, No. 10, 3 September 2001, p.1573-1575
[2] P. Sibczynski et al., NUKLEONIKA 2017;62(3):223

The designed SABAT system – VISED visualisation



The designed SABAT system – MCNP6 3D visualisation



Activation gamma-ray peaks of interest

Scattering

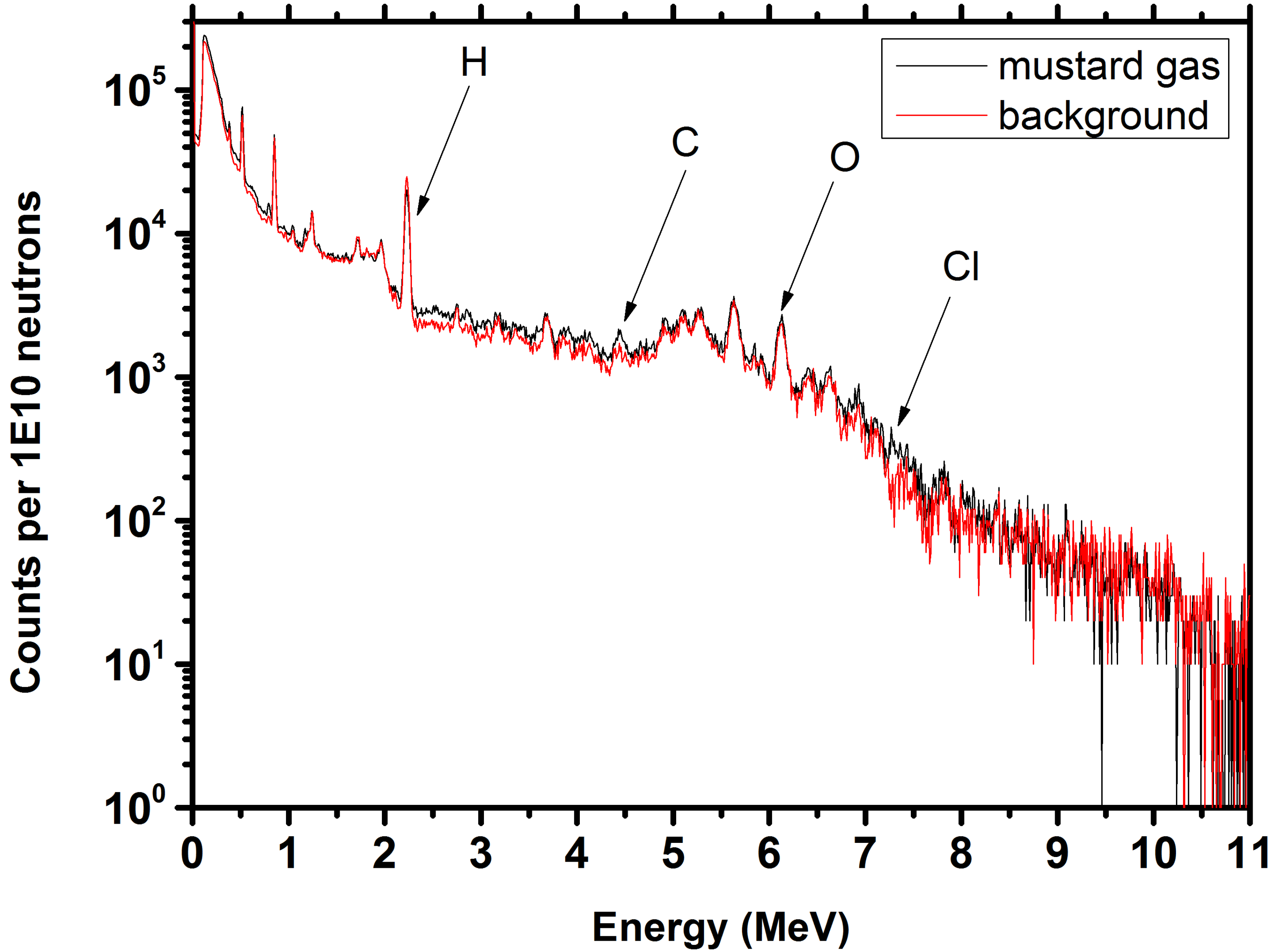
- Si: 1.78 MeV
- S: 2.23 MeV
- C: 4.44 MeV
- O: 6.13 MeV

Capture

- Cl: 0.79 MeV
- Cl: 1.17 MeV
- Cl: 1.94 MeV
- Cl: 2.12 MeV
- H: 2.23 MeV
- Cl: 6.13 MeV
- Cl: 7.79 MeV
- Cl: 8.58 MeV

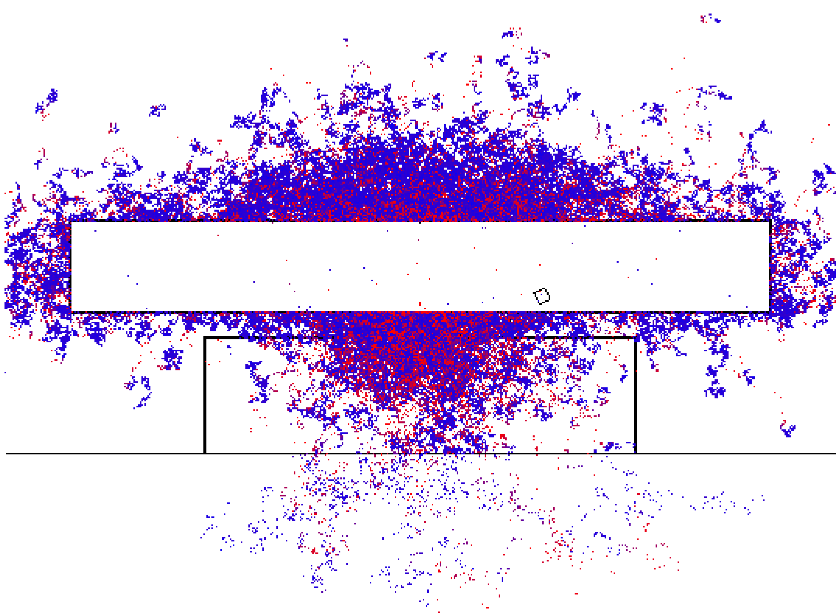
Simulated activation gamma spectra

14 MeV NG – continuous beam

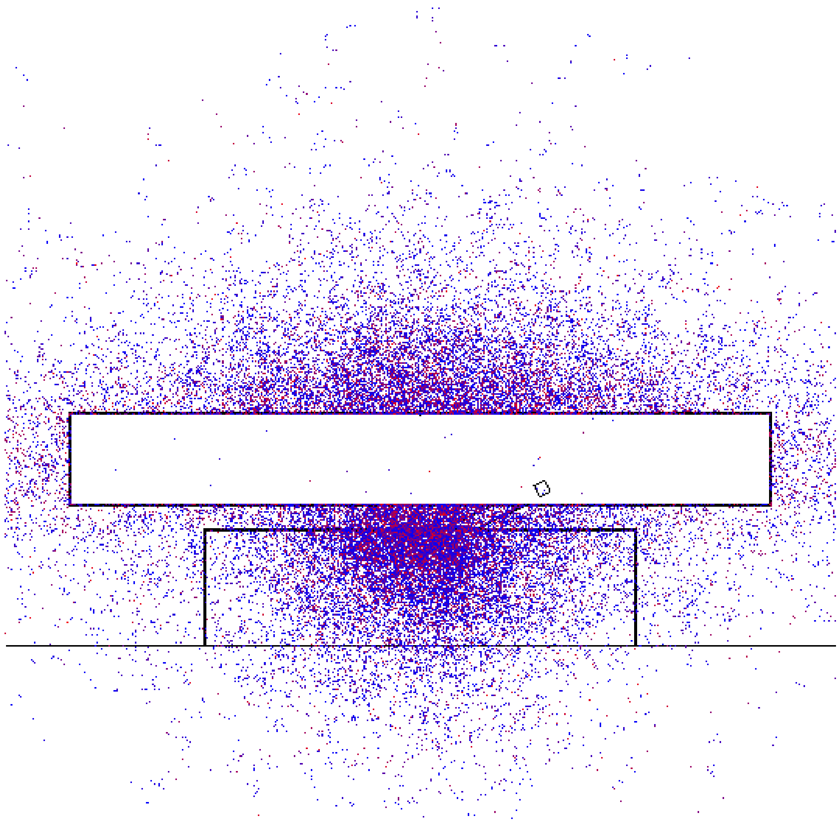


Particle tracking visualisation – 14 MeV NG continuous beam

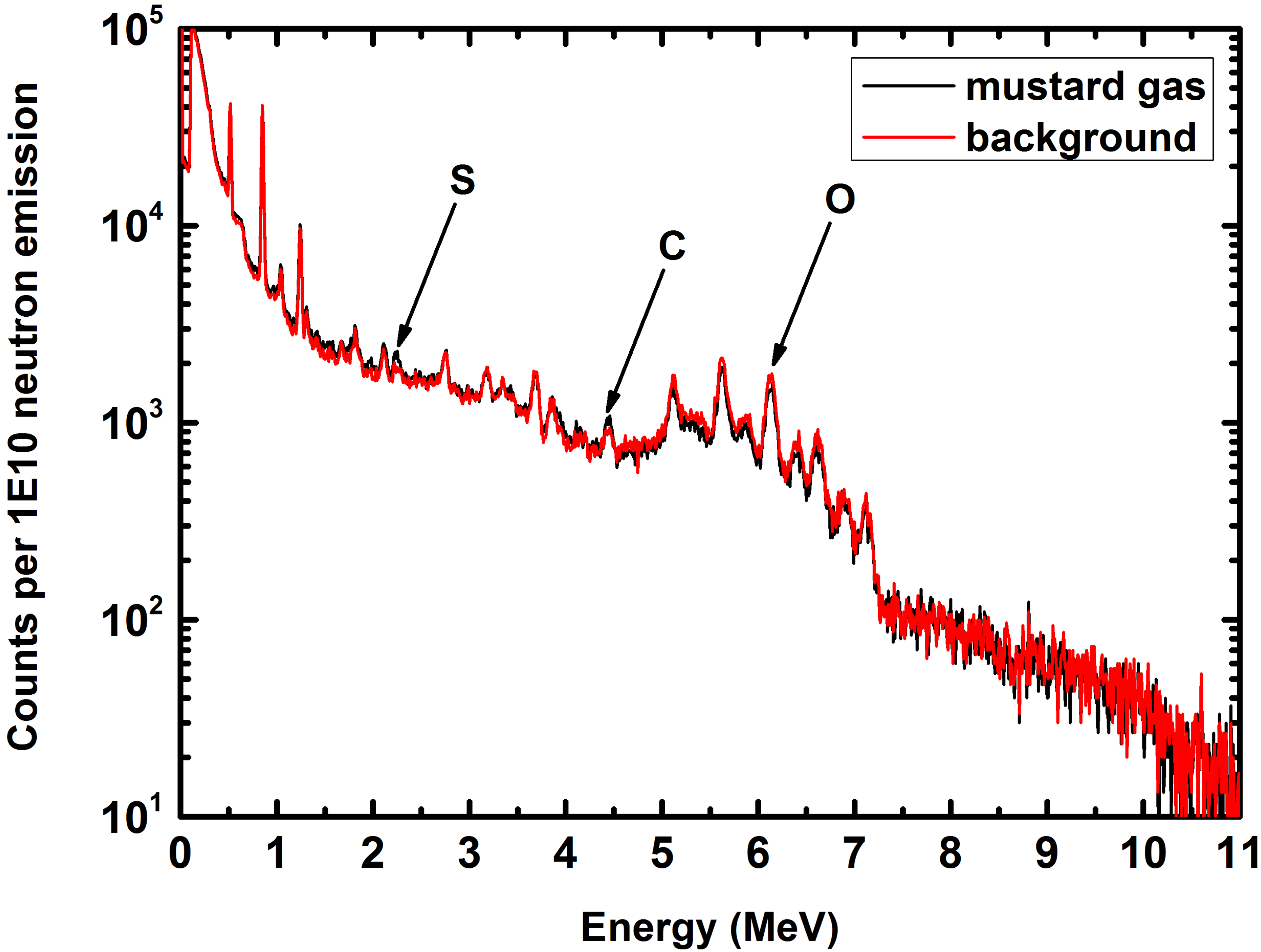
Neutrons



Gamma rays

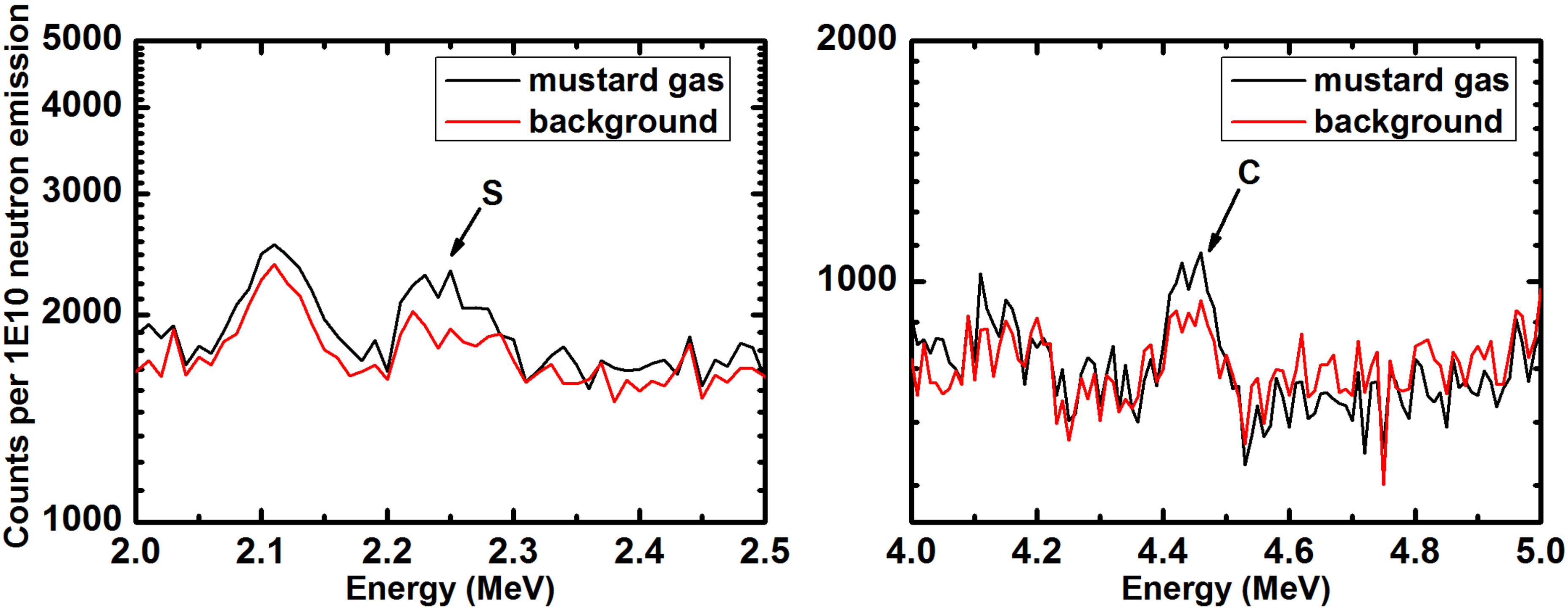


14 MeV NG pulsed beam - prompt gamma rays



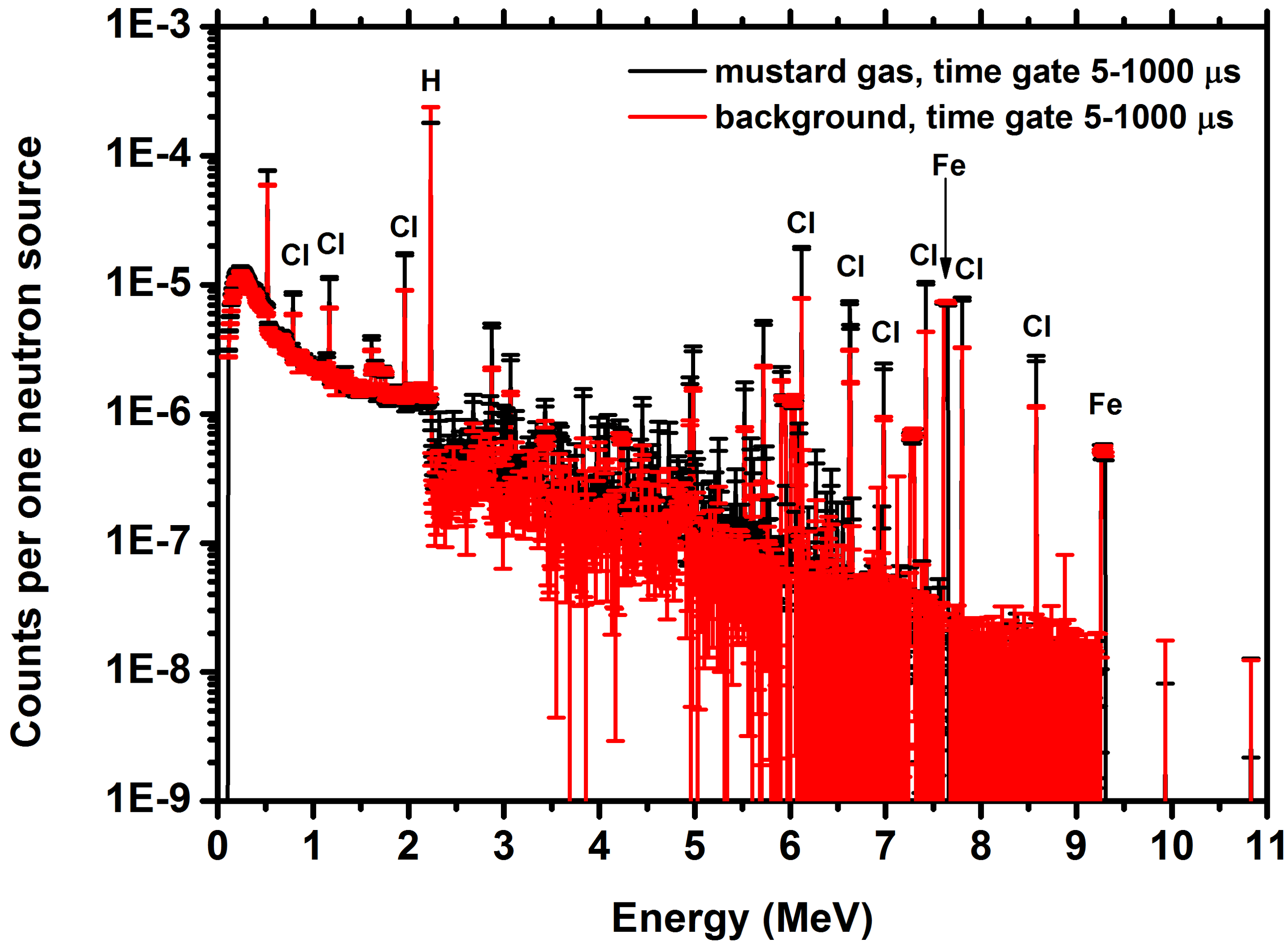
14 MeV NG pulsed beam - prompt gamma rays

Zoom in – checking the spectra details

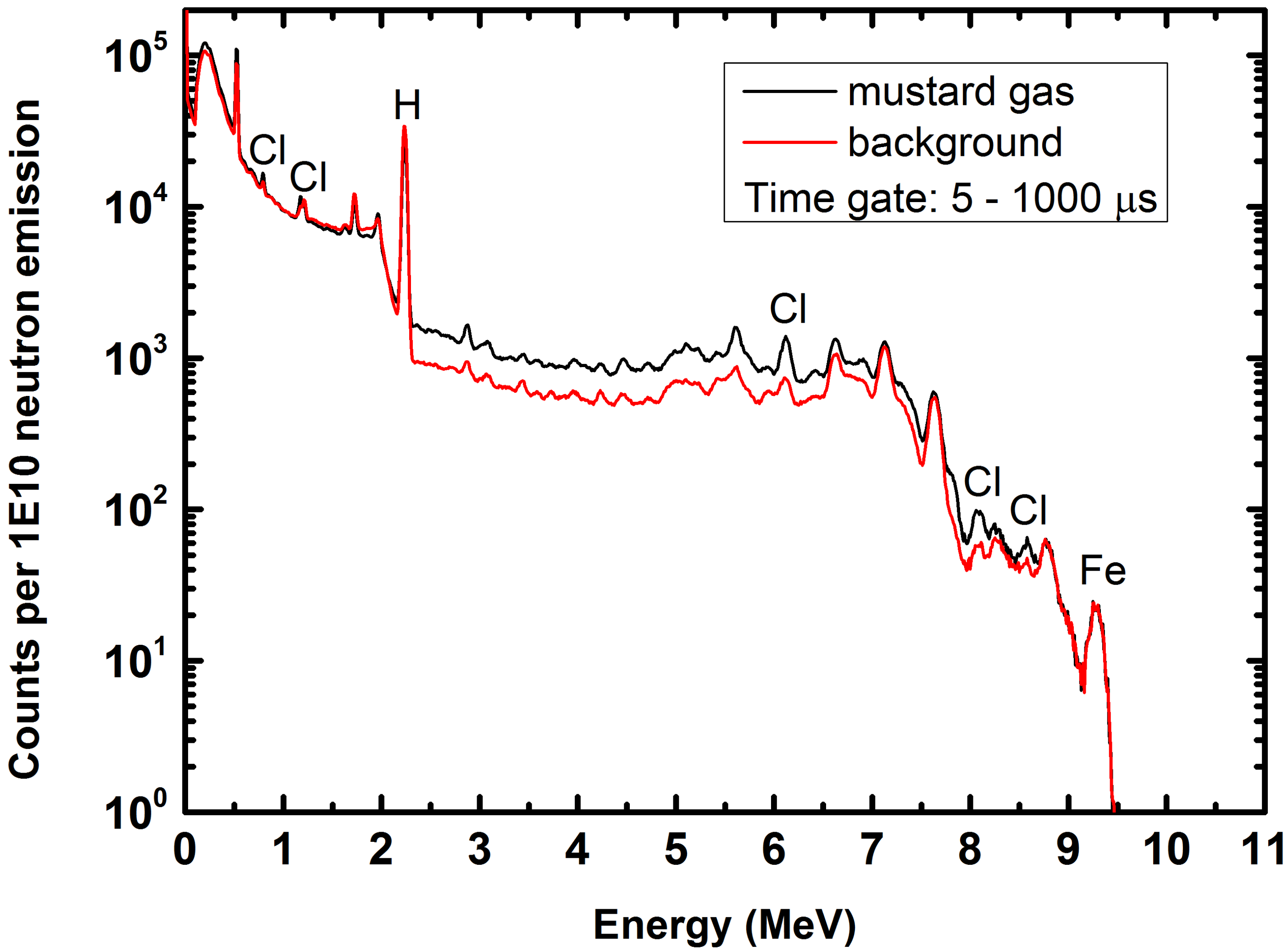


14 MeV NG pulsed beam - delayed gamma rays

Averaged gamma flux in the detector – raw output. Neutron pulse: 2 μs



14 MeV NG pulsed beam - delayed gamma rays post-processing



Stoichiometry analysis – system without radiation guides

Prompt gamma rays			
Peak ratio	Energy (MeV)	Object inspected	Stoichiometry ratio
S/O	2.23/6.13	Mustard gas	0.21 ± 0.03
Cl/O	2.12/6.13	Mustard gas	0.23 ± 0.02
C/O	4.44/6/13	Mustard gas	0.23 ± 0.02
S/O	2.23/6.13	Background	0.12 ± 0.04
Cl/O	2.12/6.13	Background	0.16 ± 0.02
C/O	4.44/6/13	Background	0.15 ± 0.02

Delayed gamma rays			
Peak ratio	Energy (MeV)	Object inspected	Stoichiometry ratio
Cl/H	2.23/6.13	Mustard gas	0.052 ± 0.003
Cl/H	2.23/6.13	Background	0.016 ± 0.002

Stoichiometry analysis – system with radiation guides

Prompt gamma rays			
Peak ratio	Energy (MeV)	Object inspected	Stoichiometry ratio
S/O	2.23/6.13	Mustard gas	0.36 ± 0.04
Cl/O	2.12/6.13	Mustard gas	0.45 ± 0.04
C/O	4.44/6/13	Mustard gas	0.31 ± 0.03
S/O	2.23/6.13	Background	0.22 ± 0.04
Cl/O	2.12/6.13	Background	0.29 ± 0.02
C/O	4.44/6/13	Background	0.19 ± 0.04

Delayed gamma rays			
Peak ratio	Energy (MeV)	Object inspected	Stoichiometry ratio
Cl/H	2.23/6.13	Mustard gas	0.053 ± 0.003
Cl/H	2.23/6.13	Background	0.014 ± 0.002

Summary

- Initial conceptual design study in Geant4 publlished in [3]
- We designed new MCNP model for underwater threat detection system
- Dection of neutron-capture gamma rays from Cl and use Cl/H stoichiometry analysis is the best solution for mustard gas detection at the sea bottom
- Detection of prompt gamma rays from S, Cl and C emitted from mustard gas is more complicated due to hydrogenuous environment, only 2sigma over background. Can be used only as a secondary inspection, when Cl/H raise alarm
- Gamma and neutron guides used in that model increase statistics in prompt Cl, S and C peaks. Signal/background ratios for guided and unguided system are within error bars
- Future work: detection performance with other threats, investigation of other possible gamma guides, comparison with other simulation codes

[3] M. Silarski et al., Acta Physica Polonica B, Vol. 47 (2016), No. 2 p. 497-502

Thank you for your attention!

NAA with longer neutron pulse – 5% duty time