

Radiation saves lives: the use of Neutron Activation Analysis in detecting hazardous materials and in the BNCT cancer therapy

Michał Silarski
Jagiellonian University



From imaging algorithms to quantum methods Seminar,
02.03.2026



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Introduction

❖ Neutrons: particles with great application potential

✓ highly penetrating (nondestructive probes)

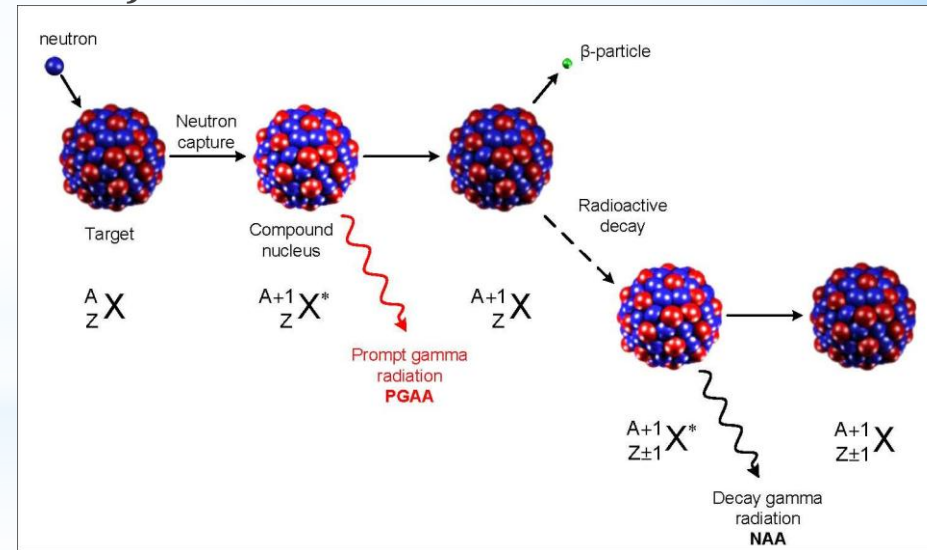
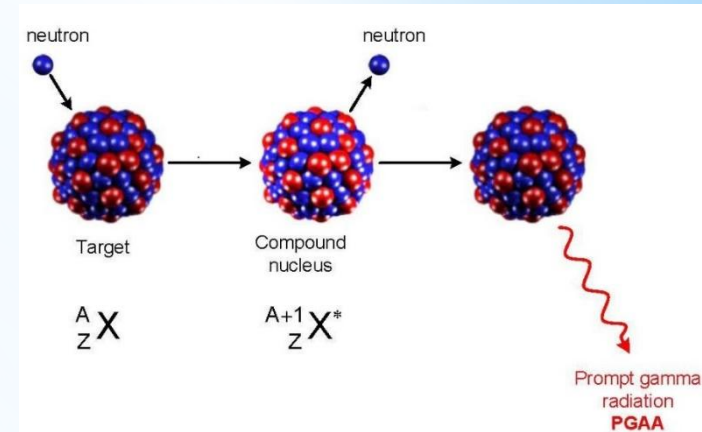
✓ „sensitive” to light atoms

❖ Some applications:

✓ Neutron radiography & scattering

✓ Oncology (neutron therapy, breast cancer detector)

✓ Counter-terrorism/IED detection



photograph



neutron



X-ray

<http://mnrdev2.ucdavis.edu/radiography.html>



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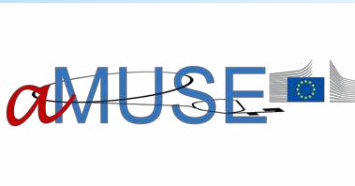
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*PART I: Underwater non-invasive threads detection



* Motivation

Skagerrak

ESTONIA

LATVIA

Unknown amount of sunken chemical weapons is scattered across the Baltic Sea... and not only!

LITHUANIA

Bornholm Basin

Gdansk Deep

Little Belt

RUSSIA



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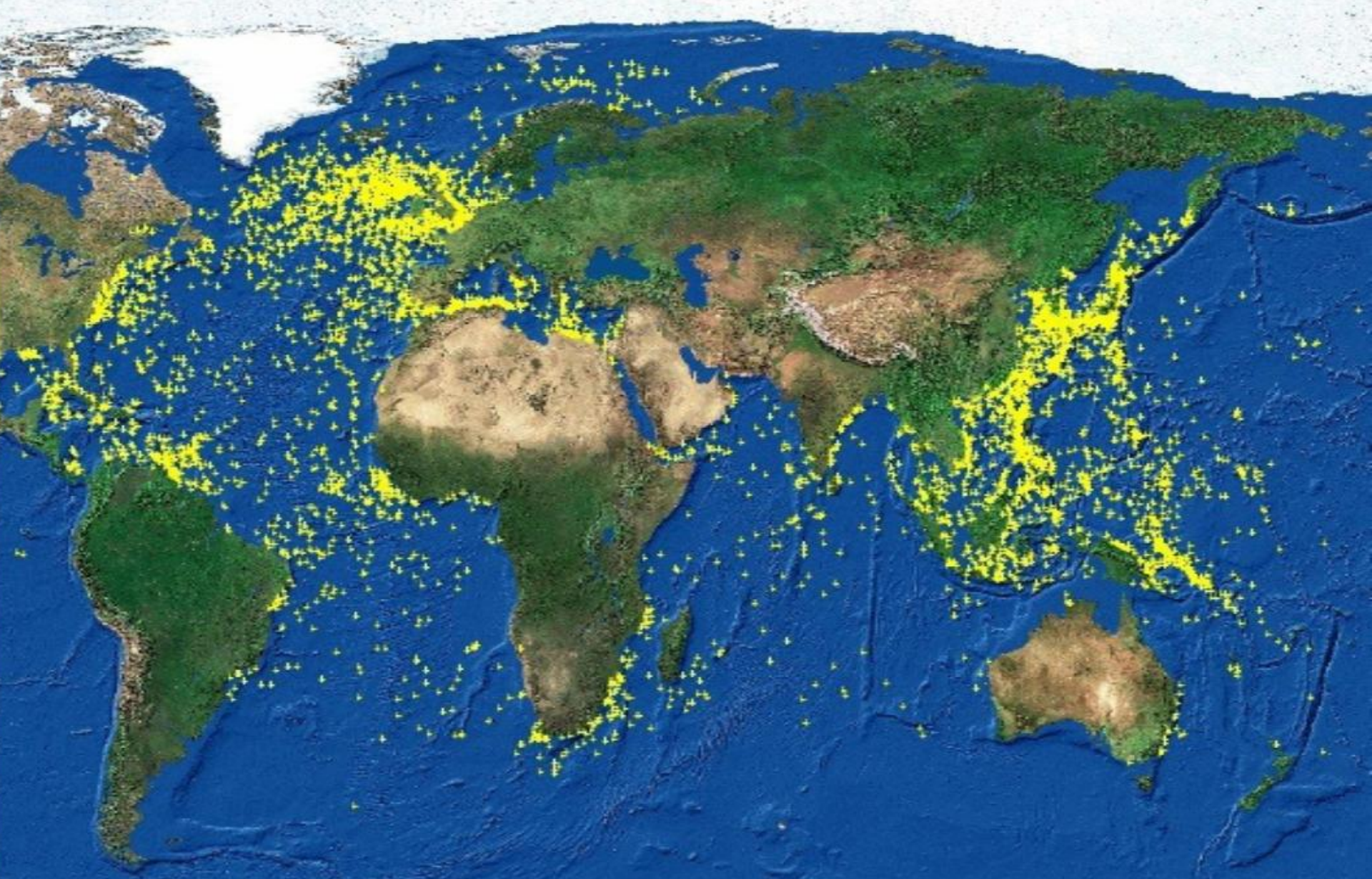


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V. Valkovic et al. 'Surveyor': An Underwater System for Threat Material Detection. International Atomic Energy Agency (IAEA): IAEA (2010).



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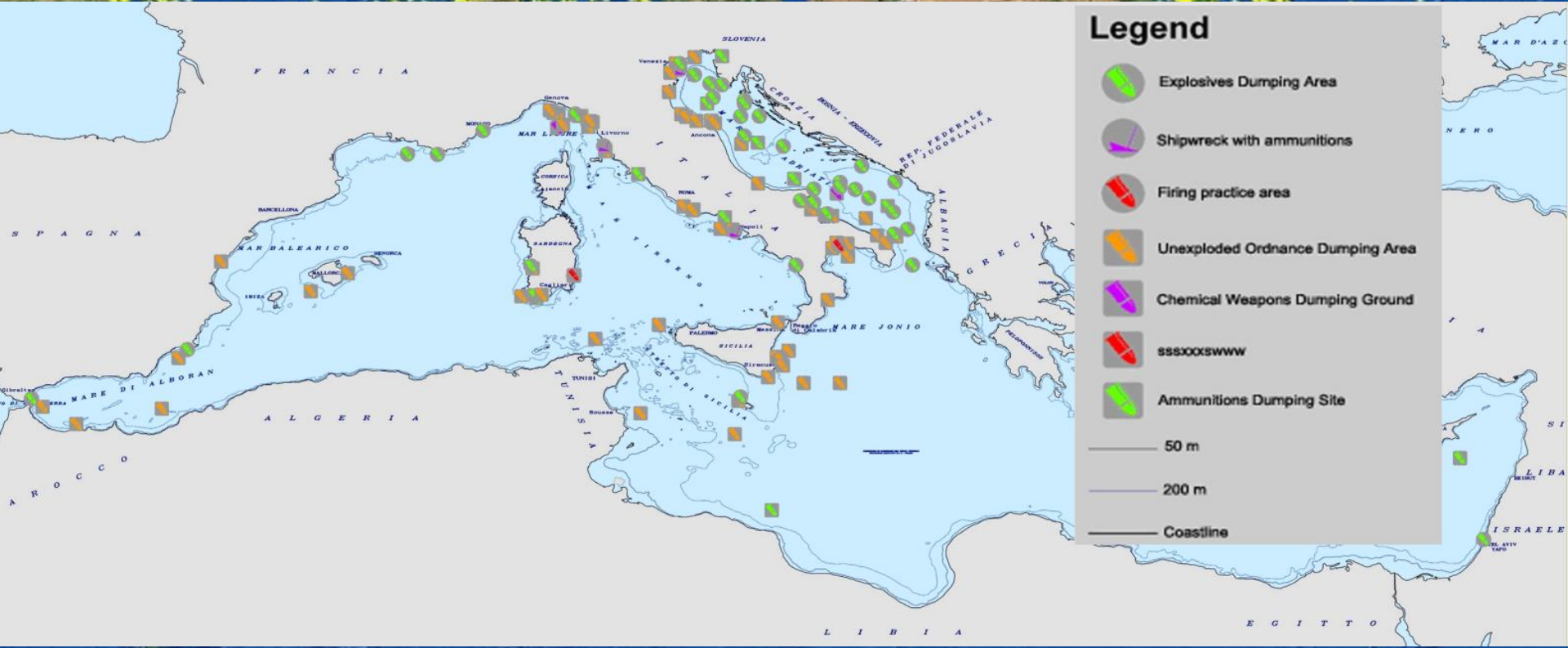


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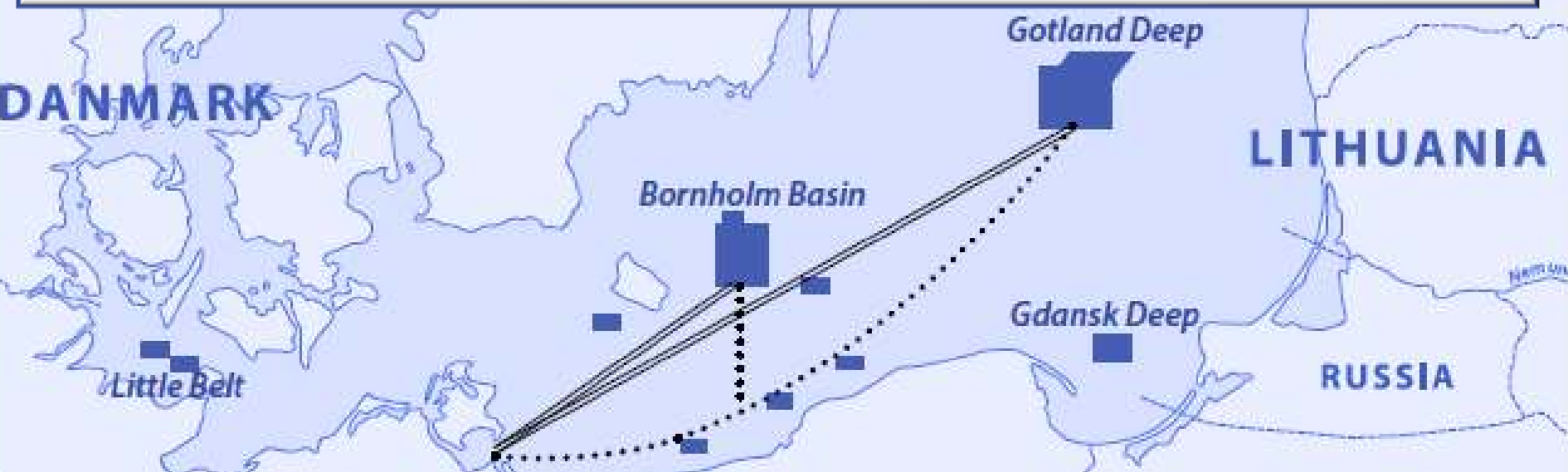


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* Motivation

- ❖ Menace to merchant navy
- ❖ Serious threat for people and environment
(„Fake amber” on the coast, mustard gas „fished” out of the sea)
- ❖ Clearing the sea bottom due to the construction of Nord Stream gas pipeline : 100 million euro



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Detection methods for underwater hazardous materials: sonars / robots

- ❖ Recognition of shapes and density of objects (“chemically blind” methods)
- ❖ They usually require confirmation by a qualified sapper



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Detection methods for underwater hazardous materials: sonars / robots

- ❖ Recognition of shapes and density of objects ("chemically blind" methods)
- ❖ They usually require confirmation by a qualified sapper
- ❖ Expensive, inefficient and slow

Possible alternative/improvement: Neutron Activation Techniques



* Neutron Activation Techniques

Novel methods of **nondestructive** chemical threat detection based on neutron activation:

Sending neutrons to the tested object

Detection of γ -rays originating from nuclei

Identification



High penetration allows detection of substances which are hidden in vehicles, buried, etc.



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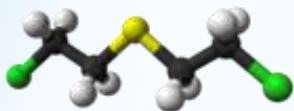
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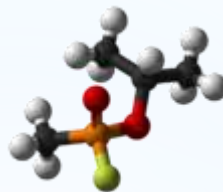
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* Motivation

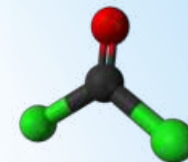
❖ Main agents to deal with:



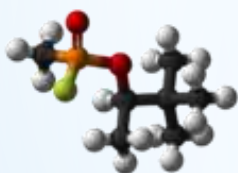
Mustard gas ($C_4H_8Cl_2S$)



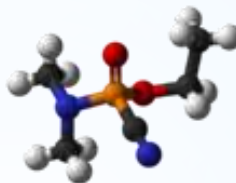
Sarin ($C_4H_{10}FO_2P$)



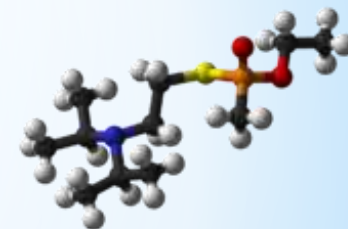
Phosgene ($COCl_2$)



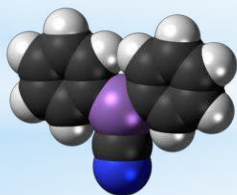
Soman ($C_7H_{16}FO_2P$)



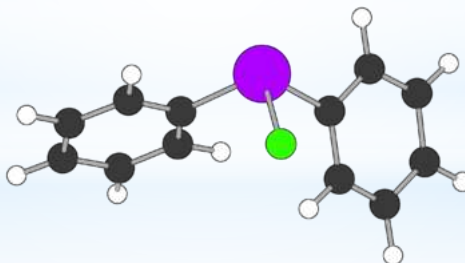
Tabun ($C_5H_{11}N_2O_2P$)



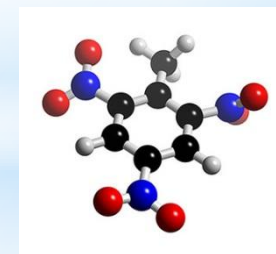
VX ($C_{11}H_{26}NO_2PS$)



Clark 2 ($C_{13}H_{10}AsN$)



Clark 1 ($C_{12}H_{10}AsCl$)



TNT ($C_7H_5N_3O_6$)



Neutron Activation Techniques

- ❖ High penetration allows detection of explosives which are hidden in vehicles, buried, etc.

Drawbacks:

- ❖ Small cross sections for some of the elements
- ❖ Decreased mobility due to detector cooling
- ❖ High neutron flux needed
- ❖ Insensitivity to the structure of molecule
- ❖ **High neutron attenuation in water**
- ❖ **High background from oxygen and hydrogen**

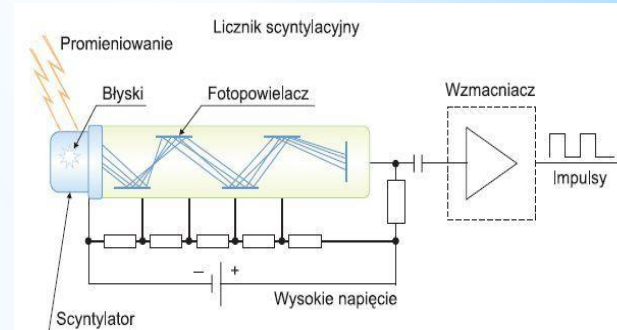
Element	Energy [MeV]	Neutron interaction process
Hydrogen	2.23	Neutron capture
Carbon	4.44	Inelastic scattering
Oxygen	6.13	Inelastic scattering
Sulfur	2.23	Inelastic scattering
Chlorine	0.79	Neutron capture
Chlorine	1.17	Neutron capture
Chlorine	2.12	Inelastic scattering
Chlorine	6.12	Neutron capture
Chlorine	7.79	Neutron capture
Chlorine	8.58	Neutron capture
Nitrogen	2.31	Neutron capture
Nitrogen	5.11	Neutron capture
Nitrogen	10.8	Neutron capture
Phosphorus	1.78	$^{31}\text{P}(n,\alpha)^{28}\text{Al}$



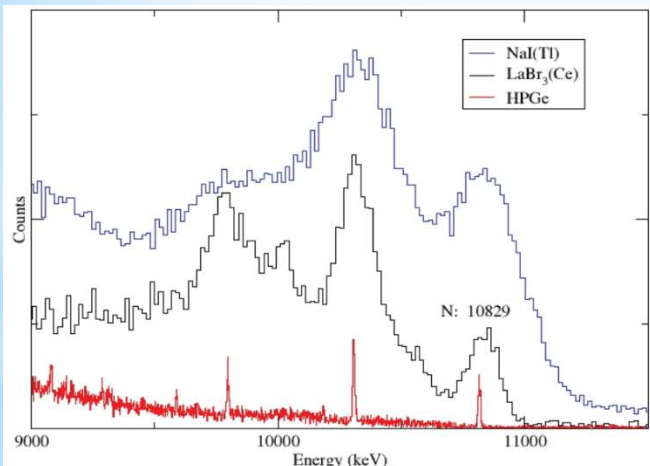
The SABAT project (Stochiometry Analysis By Activation Techniques)

- ❖ Mobility and compactness requires substitution of semiconductor detectors
- ❖ Natural candidates: inorganic scintillators:

	BGO	NaI:Tl	LaCl ₃ :Ce	LaBr ₃ Ce:Sr
Average atomic number	28	32	28	41
Density [g/cm ³]	7.1	3.7	3.9	5.3
Energy resolution (@662 keV) [%]	12	7	3.3	2.8



<https://automatykab2b.pl/technika/2306-pomiary-izotopowe-w-przemysle#.WITTFDeDMaE>



IEEE Nuclear Science Symposium, San Diego, CA, 10/29/2006, 11/04/2006



<http://irtech.pl/detektory/241-detektory-polprzewodnikowe-hpge-i-sili.html>



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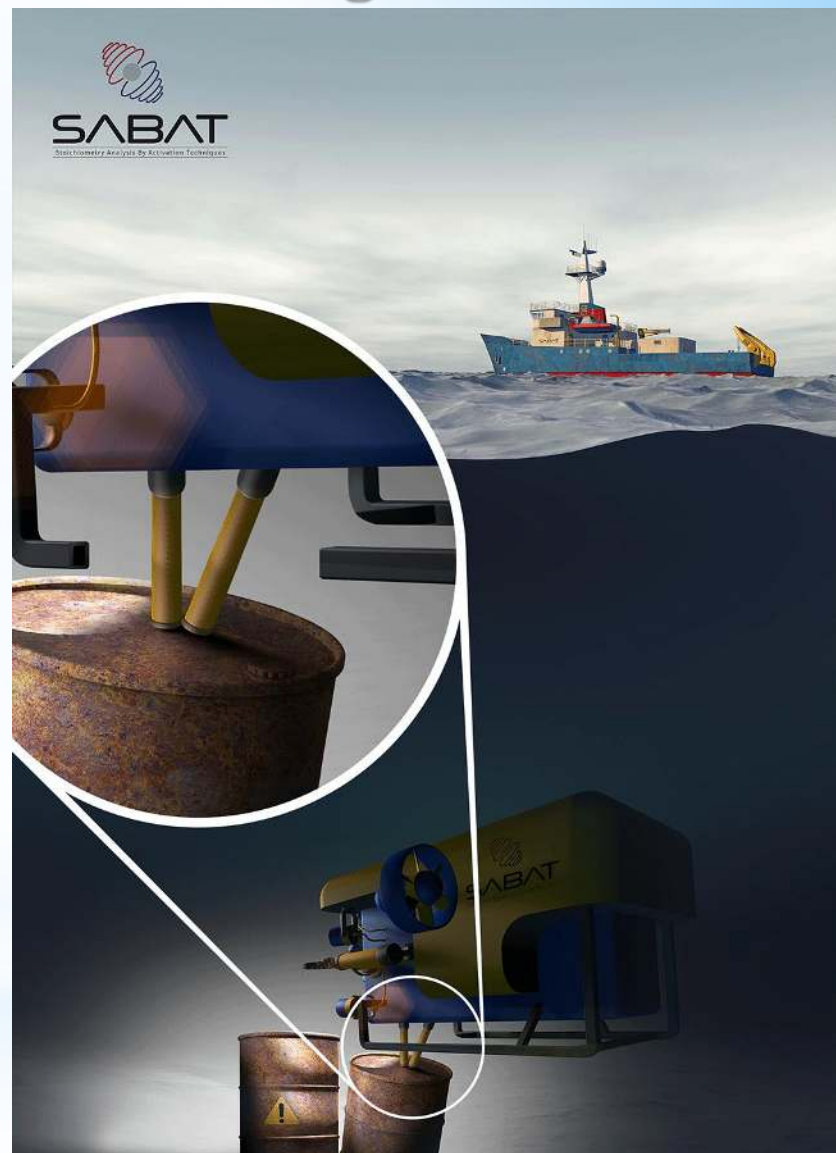


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Non-invasive detection of hazardous materials using neutron beams

- ❖ **The SABAT project (Stoichiometry Analysis By Activation Techniques)**
- ❖ The 14.1 MeV neutron generator with α particle detection
- ❖ Neutron and γ quanta attenuation in water minimized by guides filled with air or some other gas
- ❖ Pulsed generator & correlated α particles detection \Leftrightarrow tomographical picture of the chemical composition
- ❖ Changeable position, length and orientation of guides
- ❖ Position sensitive detector (**scintillator**)

(M. Silarski, P. Moskal, Patent PL 223751; EP 15738491.8;US 15/509,013)



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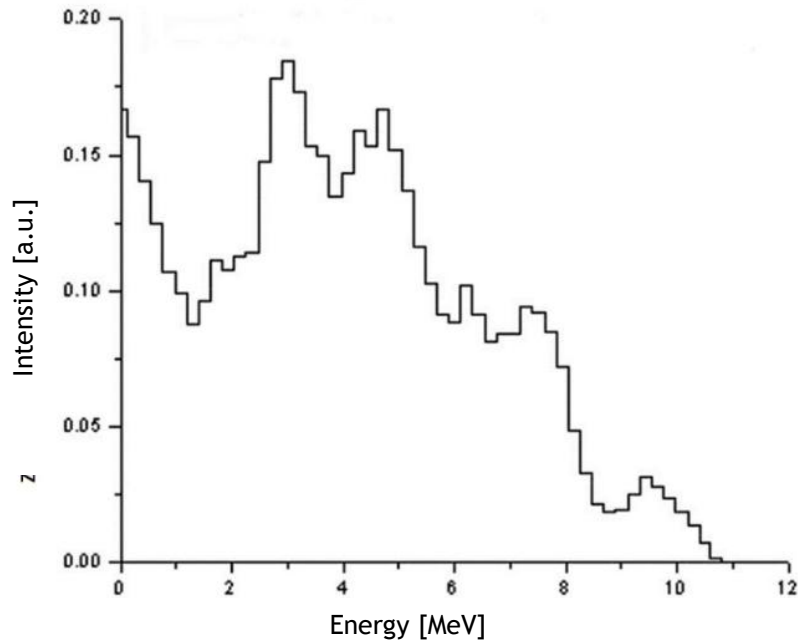


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Status of the project: first laboratory tests with a AmBe source

❖ Laboratory tests with the AmBe source

- detector ~ 15 cm from the sample
- Baltic Sea sample (4.7 kg, 5-10% of heavy fuel)
- picric acid (1.3% solution, 1 gal)
- water (~ 6 kg)
- 2"x2" LaBr₃:Ce,Sr + Hamamatsu R7723-100
- Tukan & CAEN DT5743 digitizer



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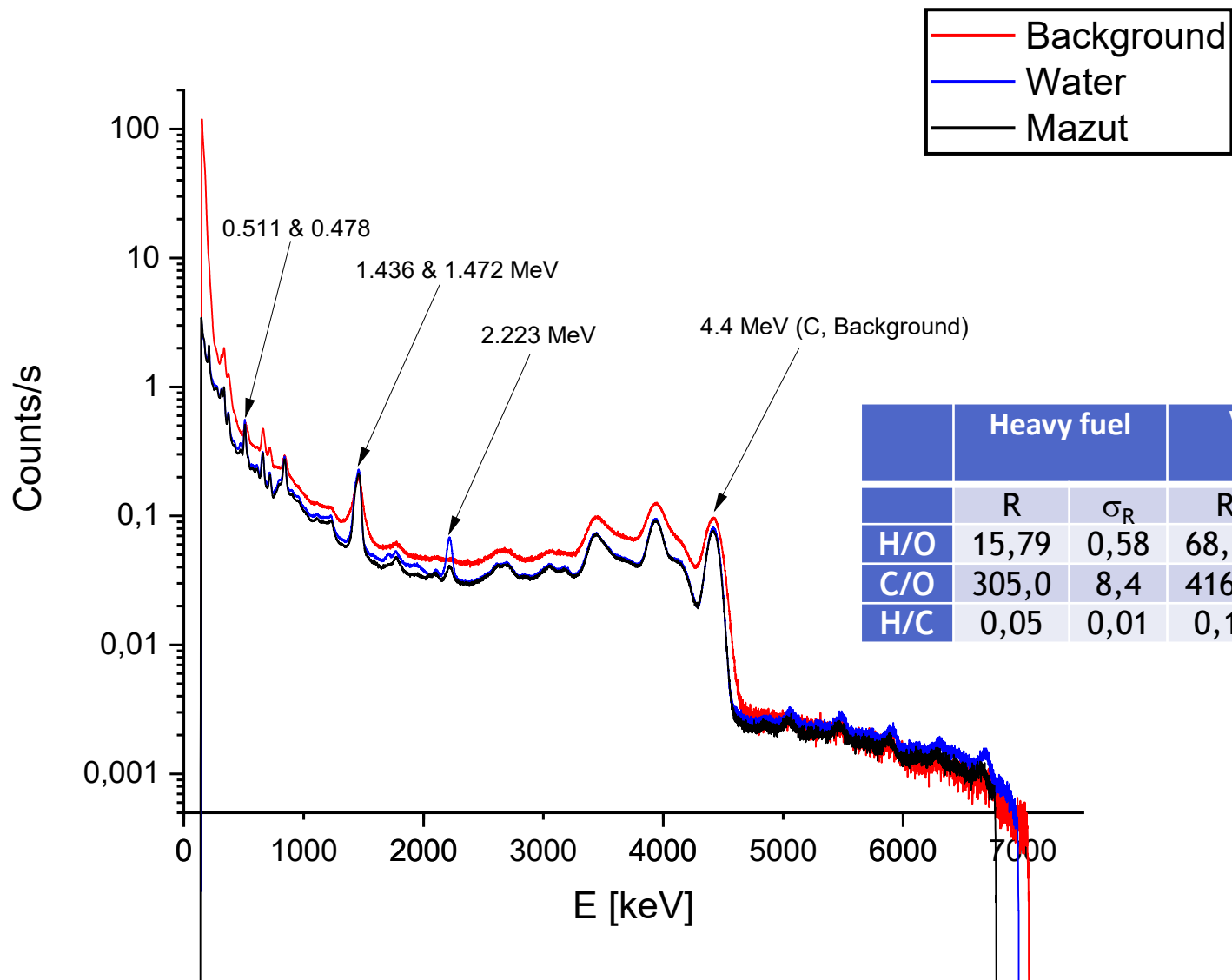
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Fundacja na rzecz
Nauki Polskiej

Status of the project: first laboratory tests with a AmBe source

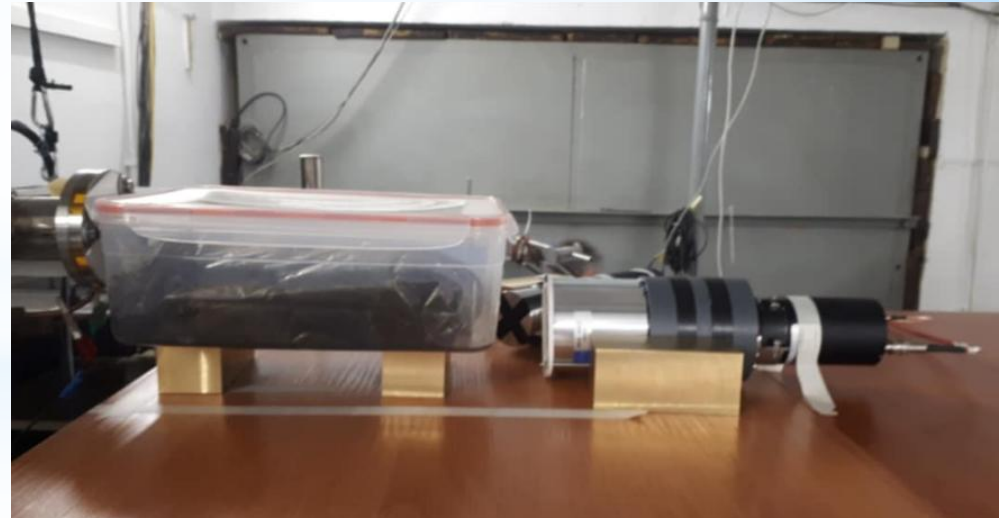
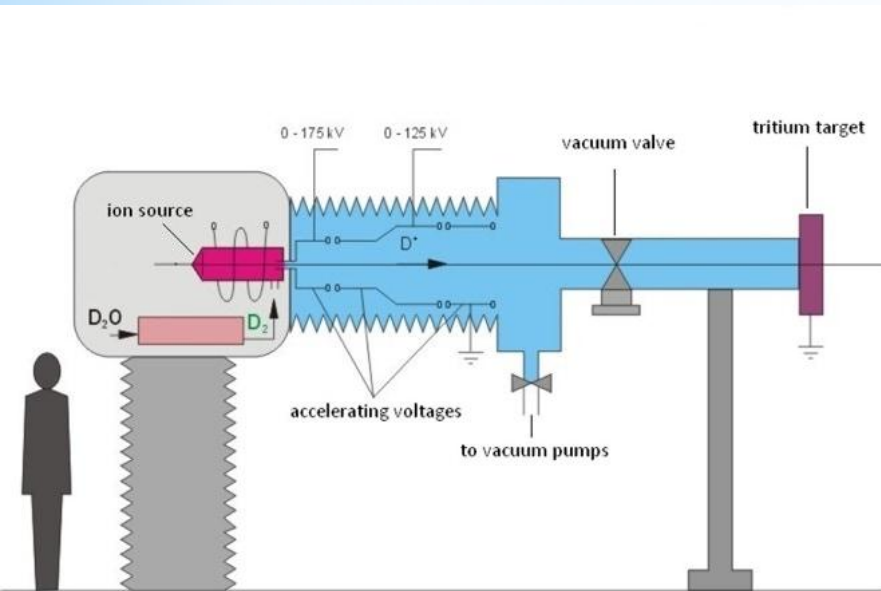


	Heavy fuel		Water		Picric Acid (C ₆ H ₃ N ₃ O ₇)	
	R	σ _R	R	σ _R	R	σ _R
H/O	15,79	0,58	68,81	0,85	61,7	1,8
C/O	305,0	8,4	416,8	5,5	452	9,6
H/C	0,05	0,01	0,17	0,02	0,14	0,03



Status of the project: laboratory tests with a DT generator

- detector ~ 15 cm from the sample
- Baltic Sea sample (4.7 kg, 5-10% of heavy fuel)
- Melamine (~1 kg)
- Boric acid (~ 0.3 g)
- 2"x2" & 3"x3" LaBr₃:Ce,Sr + Hamamatsu R7723-100
- Nucliflare



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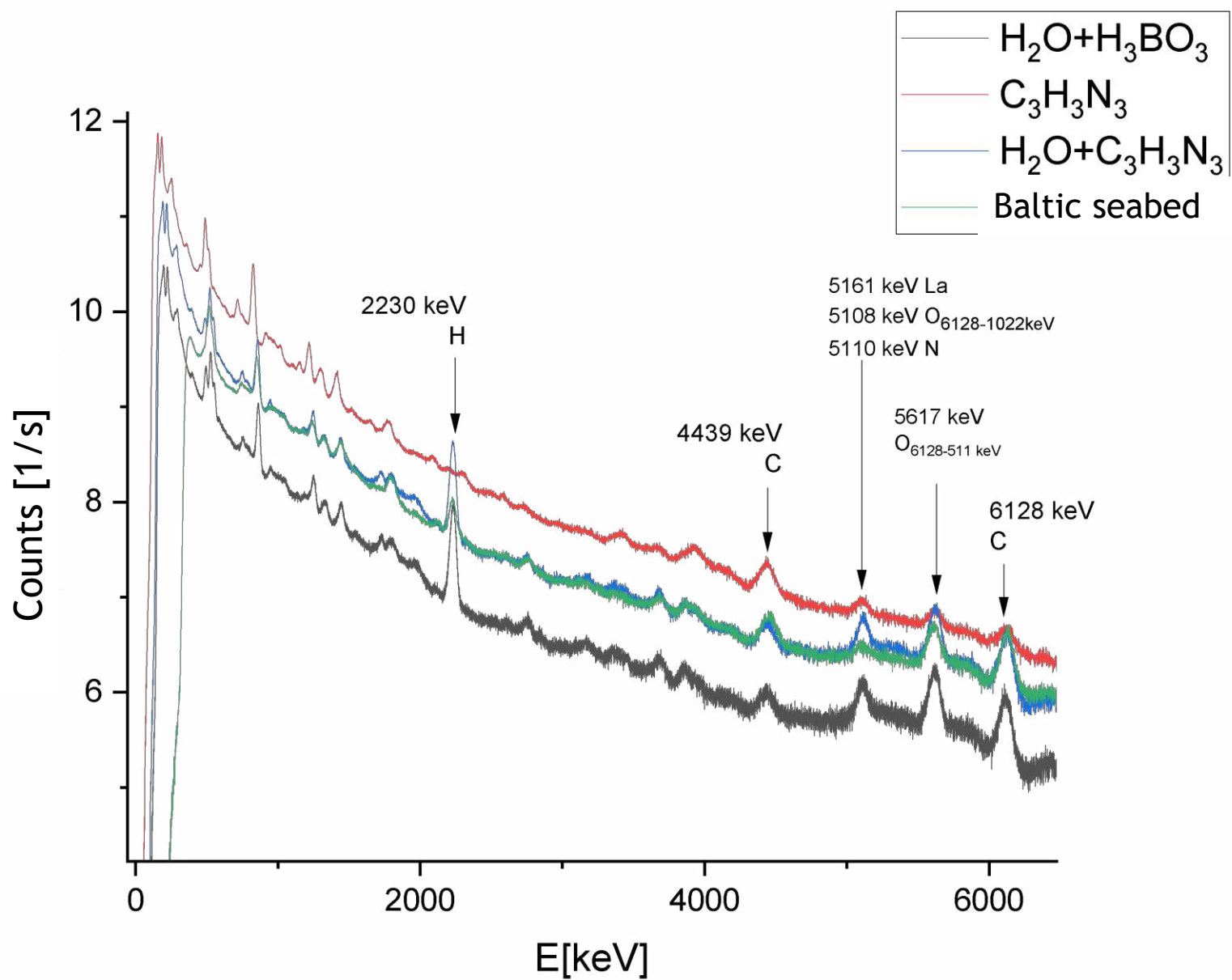


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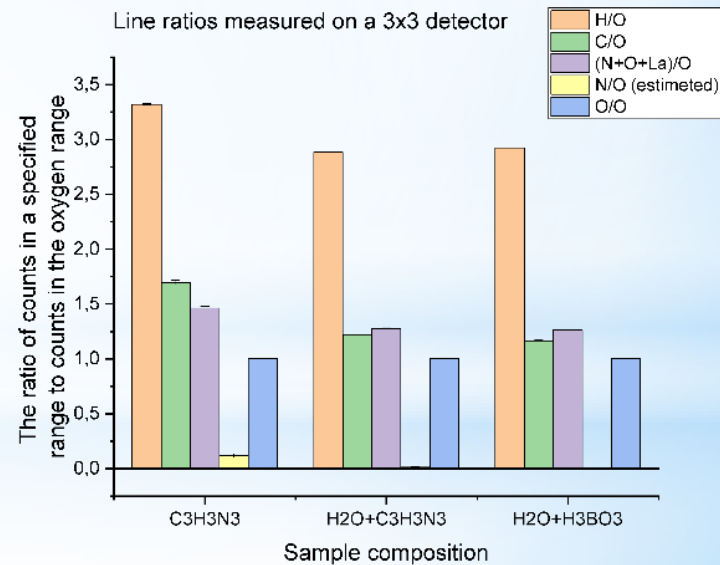
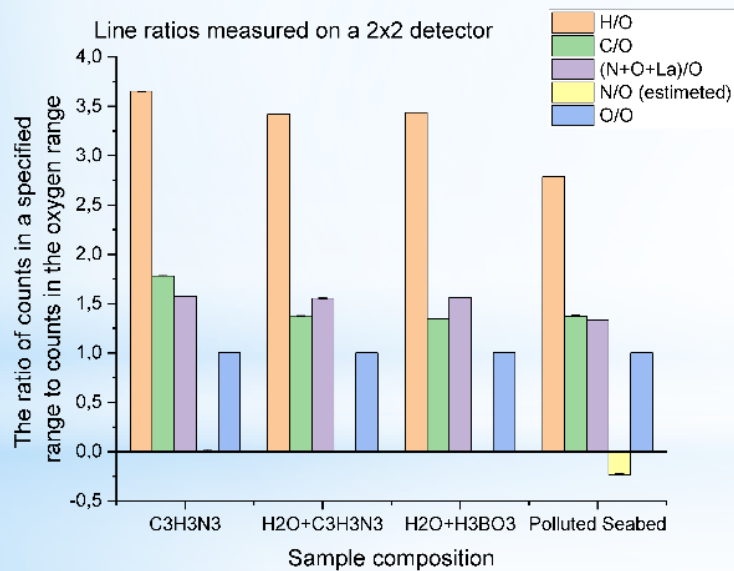
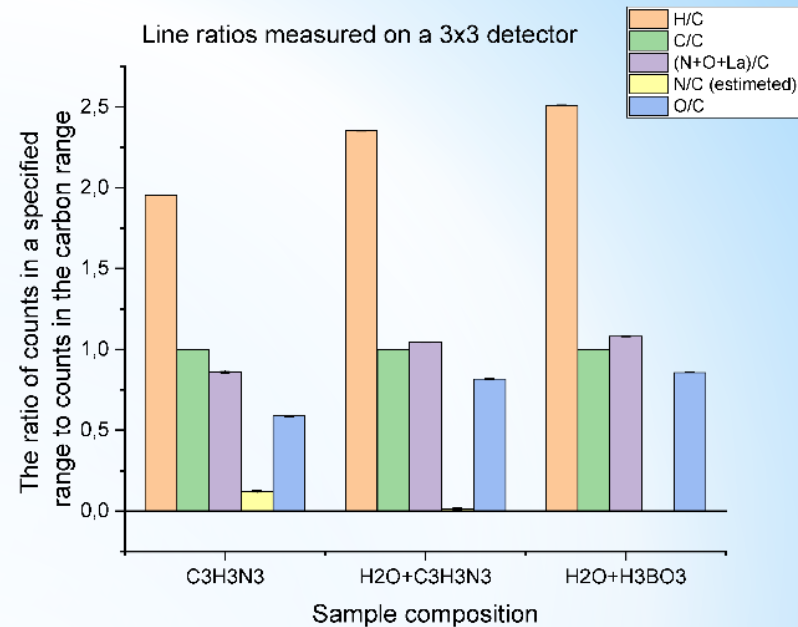
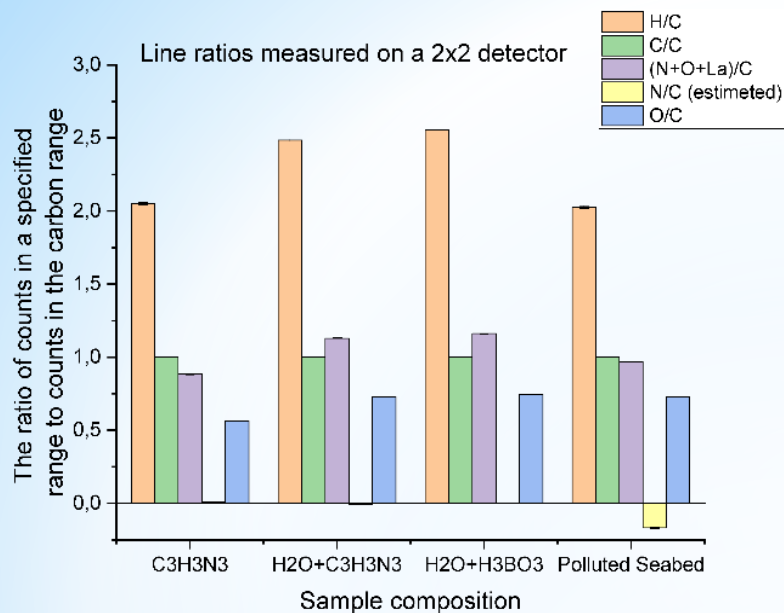


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* PART II: Boron Neutron Capture Therapy

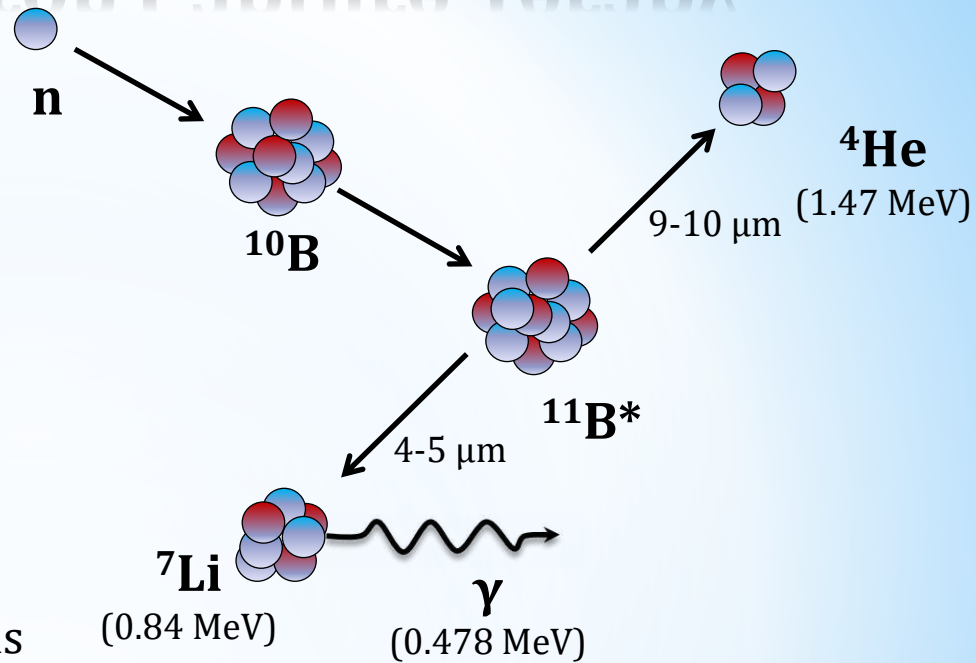


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The Boron Neutron Capture Therapy

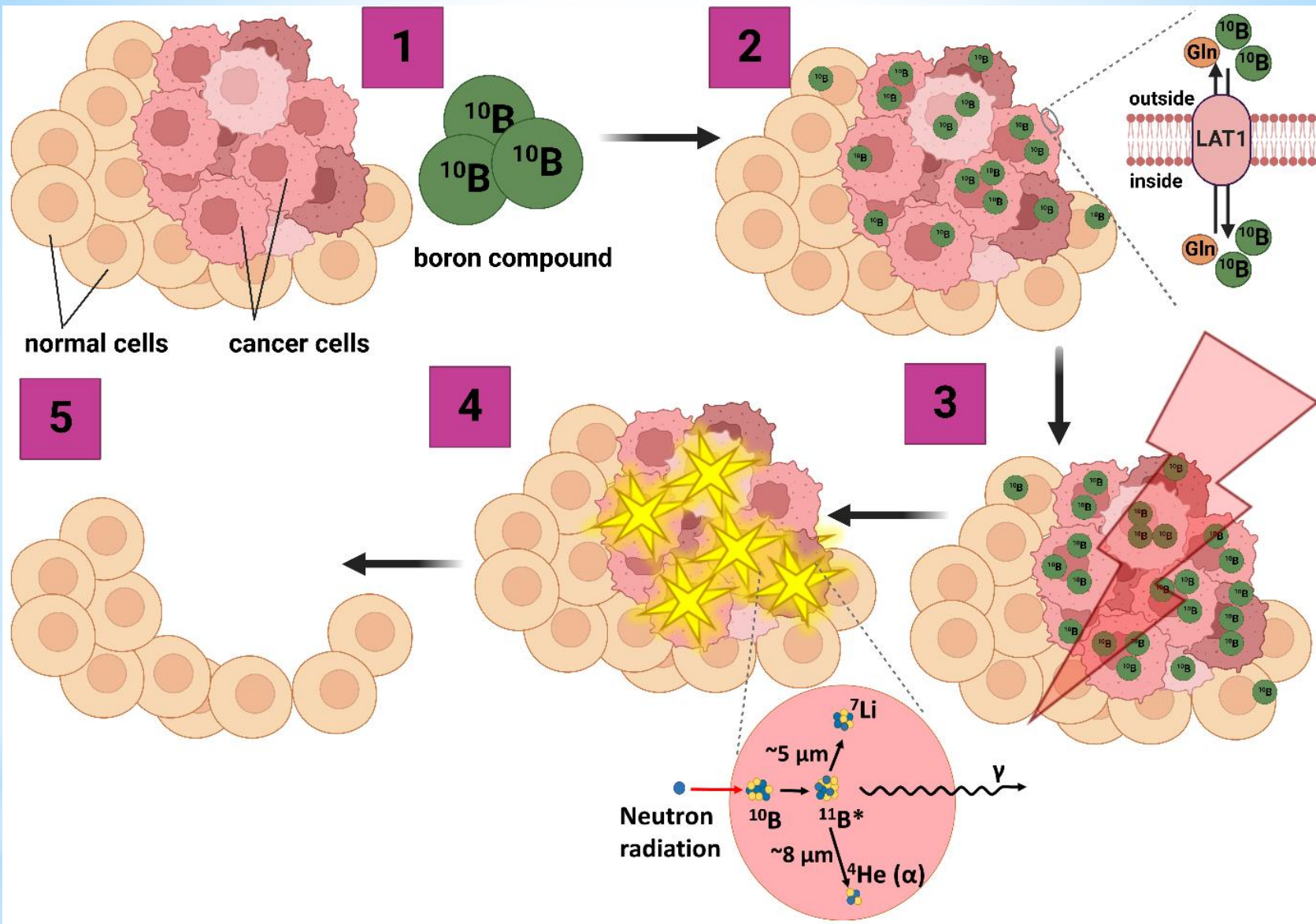
- ❖ Therapy used against highly malignant and therapeutically resistant tumors:
 - ❖ glioblastoma multiforme
 - ❖ malignant melanoma
 - ❖ head and neck recurrent cancers
 - ❖ Malignant pleural mesothelioma
- ❖ Irradiation with (epi)thermal neutrons
- ❖ ^{10}B transferred selectively to the tumor cells



Nuclide	Reaction	σ [b]
${}^6\text{Li}$	(n, α)	940
${}^{10}\text{B}$	(n, α)	9835
${}^{155}\text{Gd}$	(n, γ)	61100
${}^{157}\text{Gd}$	(n, γ)	259000



<http://www.jsnct.jp/e/index.html>; Kawasaki Medical School



M. Szczepanek, praca doktorska, Kraków 2024



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Terapia BNCT wątroby, Pavia, 2001 jakby Sci-Fi...



Chirurgiczne usunięcie
wątroby 2 h po podaniu BPA



Przygotowywanie wątroby
do transportu do reaktora



Umieszczanie wątroby w reaktorze LENA



Prof. S. Altieri (P) & Prof. Alavi (L)
Kraków, lipiec 2022

Zdjęcia: Prof. Saveiro Altieri

*Department of Physics University of Pavia , Italy
and
National Institute of Nuclear Physics
(INFN) Section of Pavia, Italy*

**szczęśliwy Pacjent 😊
40 dni po operacji/terapii**

• A. Zonta et al. *Journal of Physics: Conference Series* **41** (2006) 484



Univ. of Pavia / Reaktor LENA
Pavia, wrzesień 2023

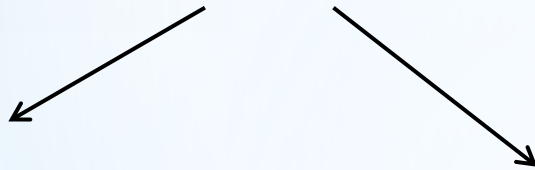


Neutron sources for BNCT

❖ Reactors

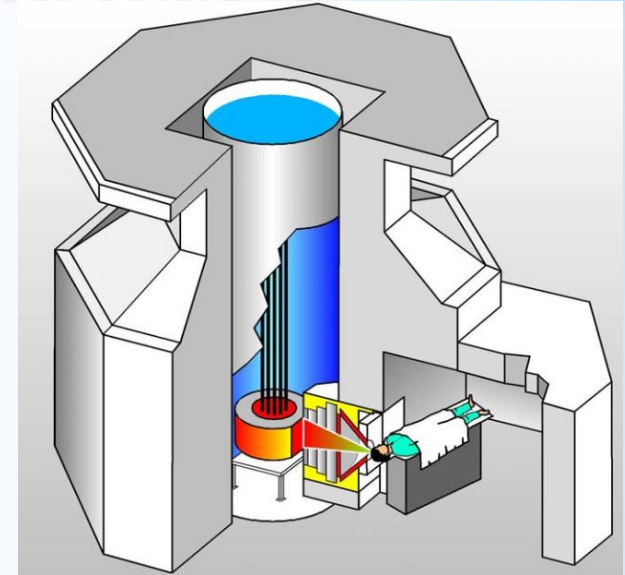
- ❖ High neutron flux (e.g. Maria: $\sim 10^{14}$ cm⁻²s)
- ❖ Expensive and complex
- ❖ low public acceptability
- ❖ require complicated licensing procedures

Reactor BNCT beams



core neutrons
(fast→epithermal)

fission converter
(thermal→ epithermal)



physicsworld

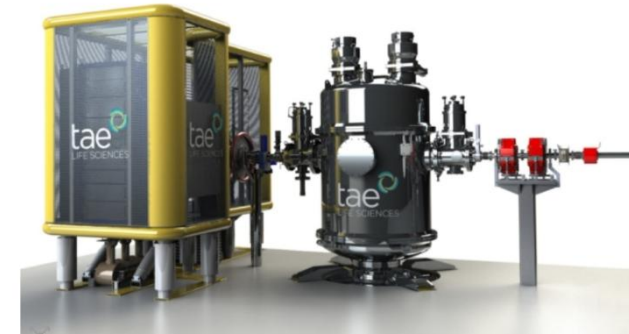


Magazine | Latest | People

RADIOTHERAPY | RESEARCH UPDATE

Boron neutron capture therapy progresses towards clinical cancer treatments

17 May 2019 Tami Freeman



❖ Accelerator sources

- ❖ Most popular reactions:
 ${}^7\text{Li}(p,n){}^7\text{Be}$ and ${}^9\text{Be}(p,n){}^9\text{B}$
- ❖ Target cooling problems for high proton intensity



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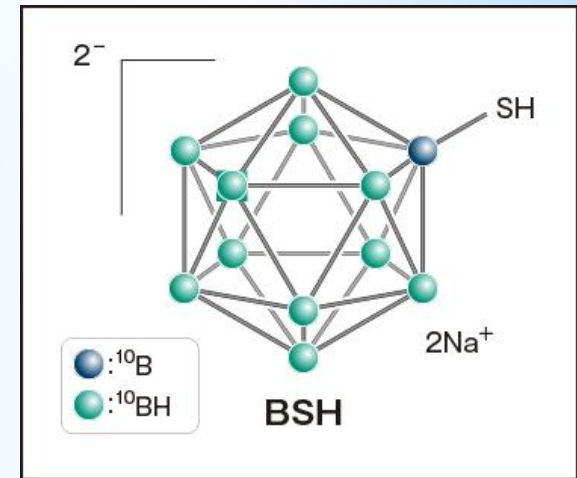
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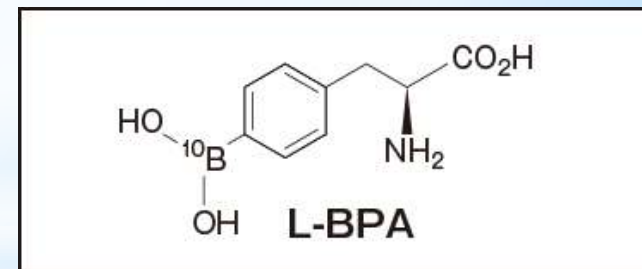
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Boron carriers

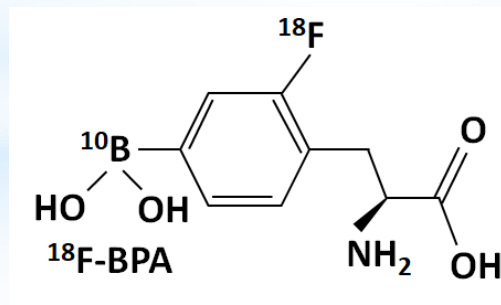
- ❖ Selective accumulation (Tumor/Normal >3) with ^{10}B concentration of 20 to 40 ppm
- ❖ Low toxicity
- ❖ Not metabolized in the tumor
- ❖ No pharmaceutical effects themselves
- ❖ BSH (disodium mercaptoundecahydrododecaborate)
 - ❖ Low accumulation inside tumor cells (it stays in the intercellular spaces)
- ❖ L-BPA (L-p-Boronophenylalanine)
 - ❖ Administered combined with a water-soluble substance such as D-fructose
 - ❖ does not accumulate in slowly proliferating malignant cells



http://www.jsnct.jp/e/about_nct/houso.html



http://www.jsnct.jp/e/about_nct/houso.html



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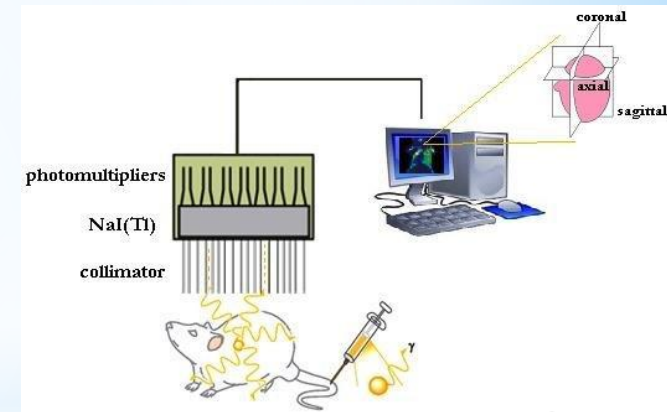
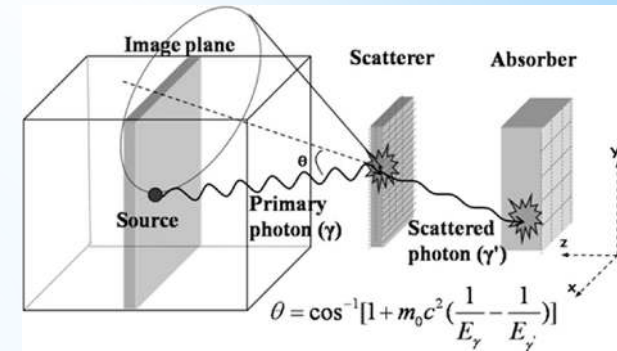
Dose & boron distribution monitoring

❖ Magnetic Resonance Imaging (MRI)

- Non-invasive imaging of boron distribution
- Sensitive to ^{10}B and ^{11}B isotopes

❖ Positron Emission Tomography

- Boron carrier labeled with β^+ active element:
- L-F-Boronophenylalanine [Imahori Y. et al. J Nucl Med. 39 (1998) 325]
- ^{64}Cu -labeled BSH-3R-DOTA [Y. Iguchi et al., Biomaterials 56 (2015) 10]
- Non-invasive imaging of boron distribution in the patient's body at each stage of therapy (resolution $\sim 4\text{-}6\text{ mm}$)



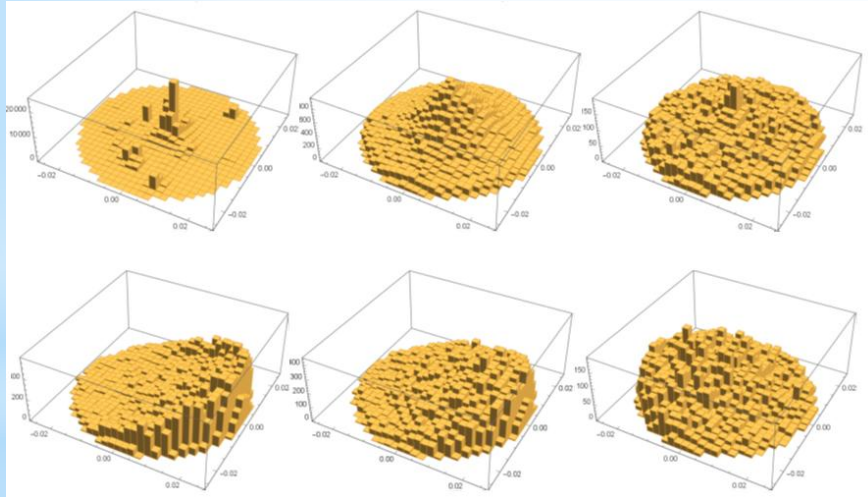
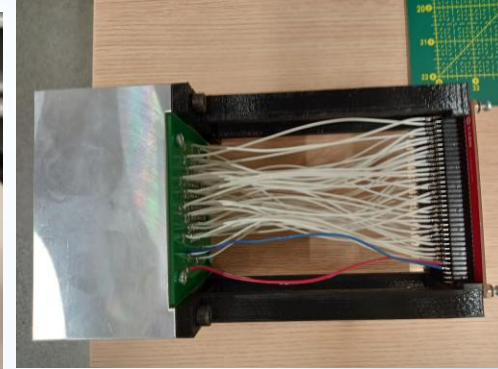
❖ Prompt Gamma Radiation Analysis

- Gamma quanta due to neutron capture on ^{10}B ($E_\gamma = 0.478\text{ MeV}$)
- Radiation from tissue activation (**H,C,N,...**)
- A fast method allowing *in vivo* imaging during the therapy



New Prompt Gamma Radiation Analysis system

- $\text{LaBr}_3:\text{Ce}$ crystal + SiMP readout
- Anti-Compton shield to suppress background
- Position reconstruction based on the distribution of optical photons (machine learning)
- DAQ based on the CAEN Citiroc 1A
- Rough separation of the 478 and 511 keV seen in the presence of background



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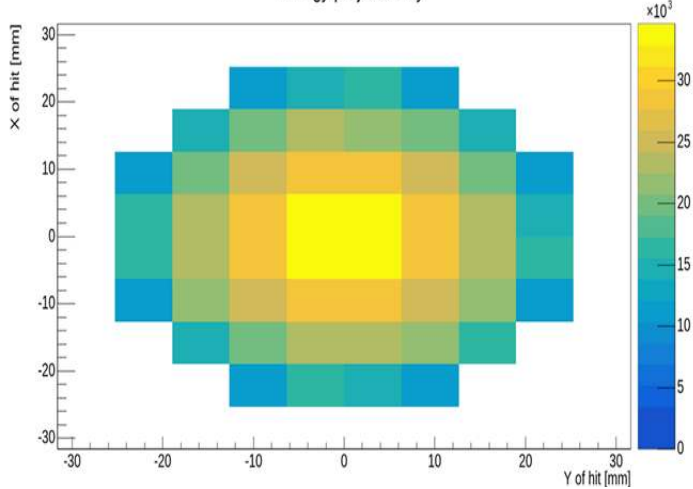


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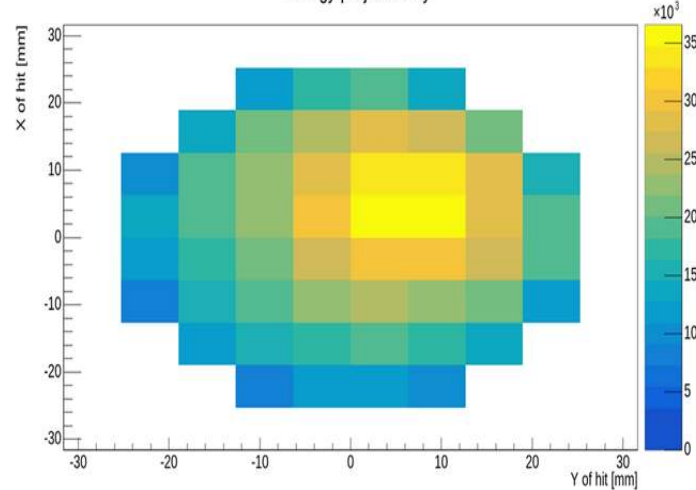
New Prompt Gamma Radiation Analysis system

❖ Realistyczne symulacje Monte Carlo (GEANT-4) dla energii 478 keV

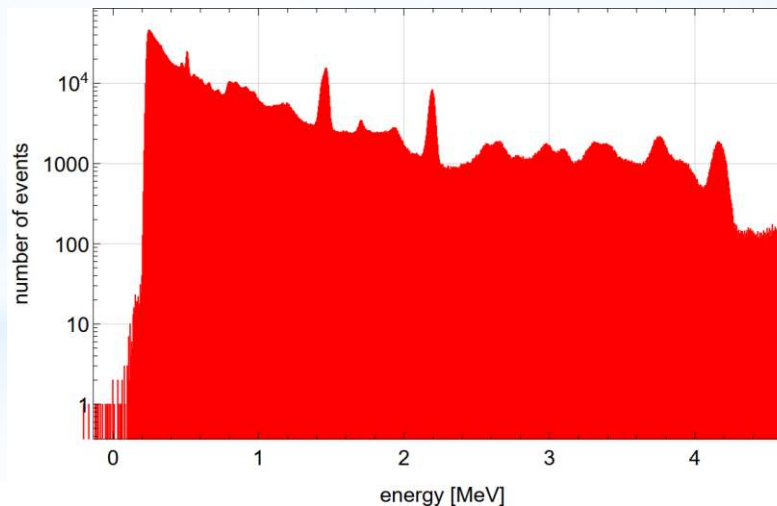
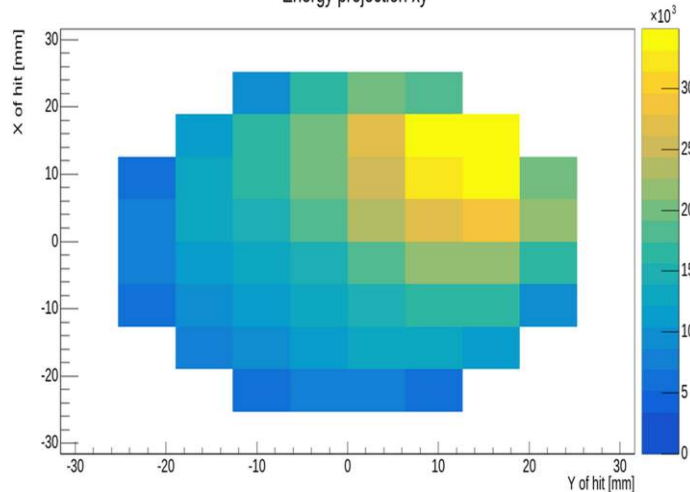
Energy projection xy



Energy projection xy



Energy projection xy



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* Thank You for attention



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