UNDERWATER DETECTION OF DANGEROUS SUBSTANCES: THE SABAT PROJECT

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on behalf of the SABAT collaboration

- Introduction
- Neutron Activation Techniques
- Application in the underwater environment
- Status of the project
- Summary

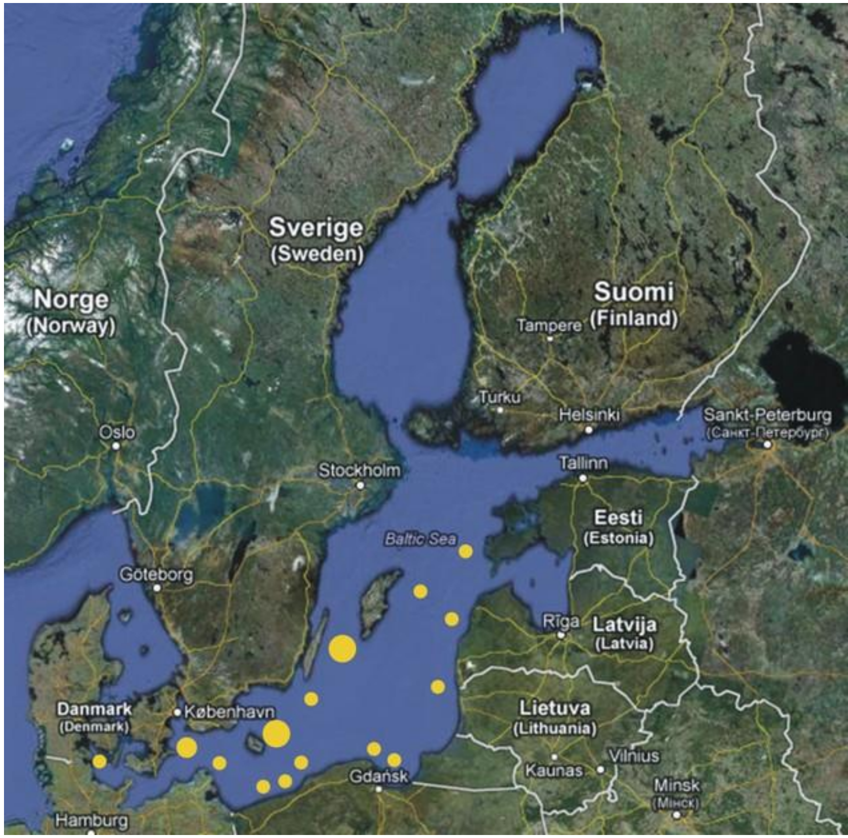
Introduction

- „Ghosts" of World Wars: ~250 kt of munition (including 65 kt of chemical agents) sunk in the Baltic Sea

- Main known contaminated areas: Little Belt, Bornholm Deep (east of Bornholm) and the southwestern part of the Gotland Deep

- **Unknown amount of chemical leftovers are spread around the Baltic Sea**

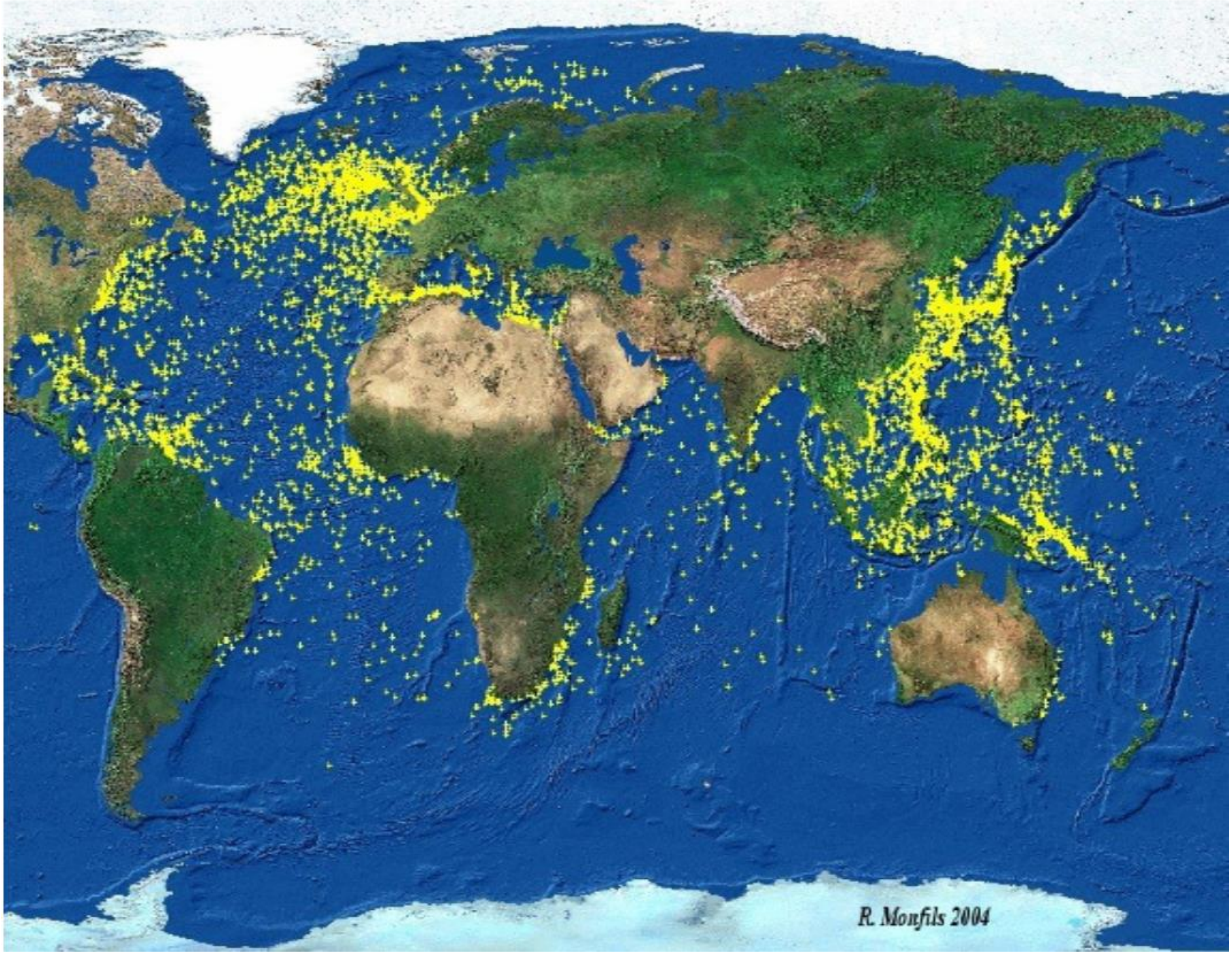
- Serious threat for people and environment
  - „Fake amber" on the coast
  - Mustard gas „fished" out the sea
  - Menace to navy
  - Genetic mutations of marine fauna



http://www.sfora.pl/polska/Napalm-w-Baltyku-Przed-katastrofa-nie-ma-ratunku-a52539

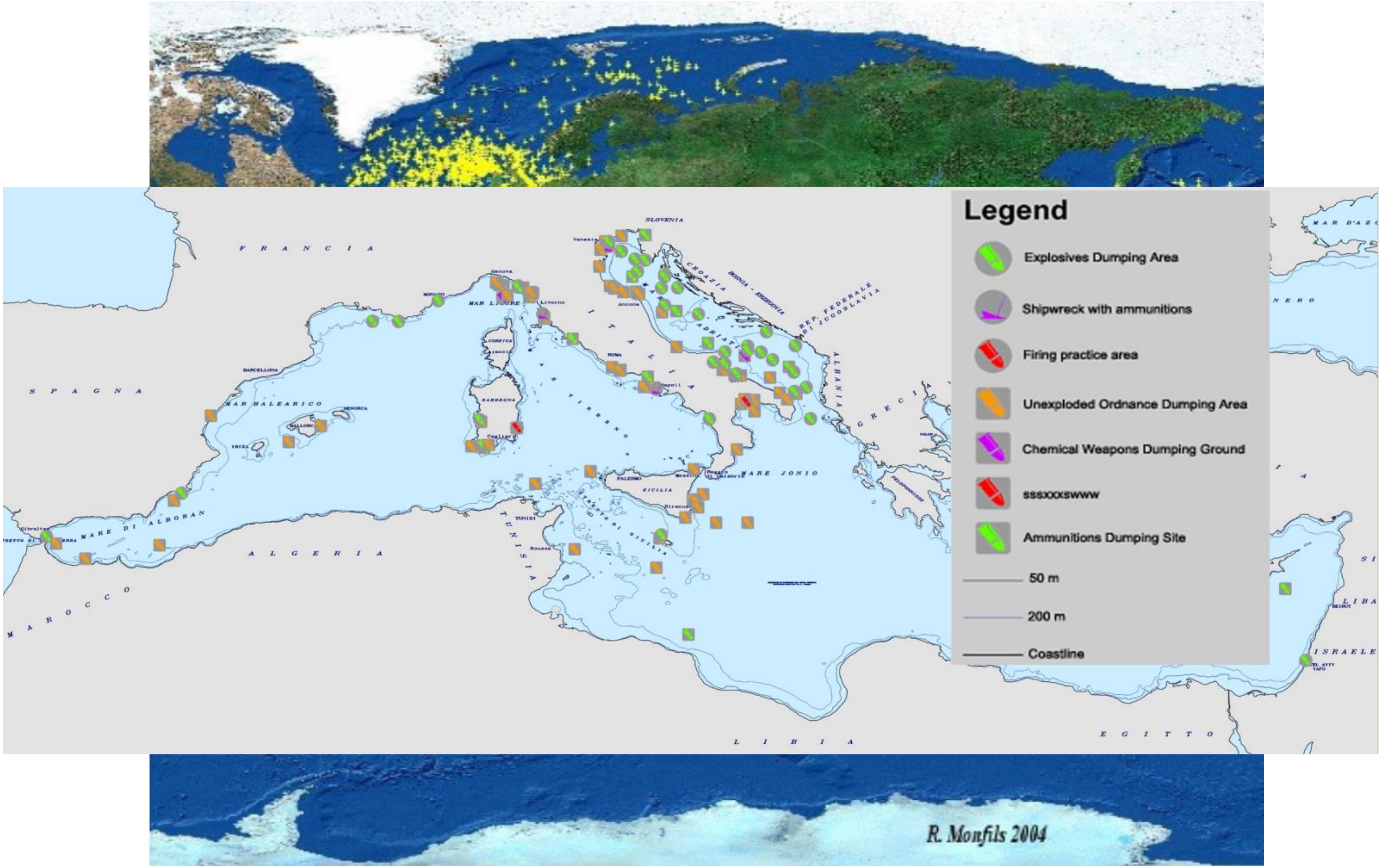
- **1/6 of the sunk munition released into Baltic = entire degradation of live in the sea and at its shores for 100 years!!**

Introduction



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

Introduction



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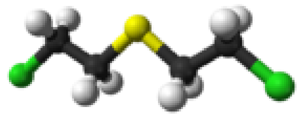
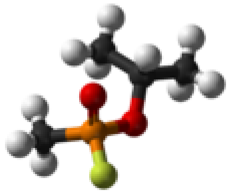
Introduction

- Main agents to deal with:

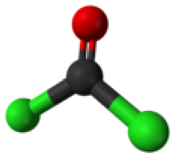
Mustard gas ($C_4H_8Cl_2S$)



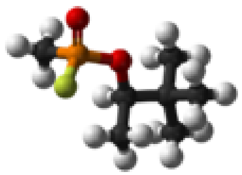
Sarin ($C_4H_{10}FO_2P$)



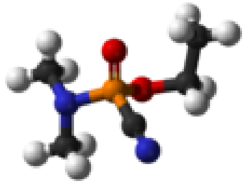
Fosgen ($COCl_2$)



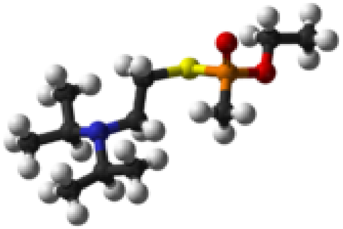
Soman ($C_7H_{16}FO_2P$)

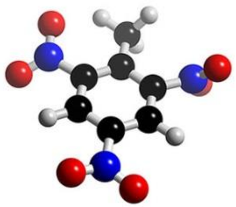


Tabun ($C_5H_{11}N_2O_2P$)



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





TNT ($C_7H_5N_3O_6$)

- Presently used detection methods:
  - Sonars (shape and localization) + diver/robot inspection (evaluation of the ammunition shell and type)
  - „By chance”: during fishing, etc.
- **High economic and environmental costs have been preventing so far any activities aiming at extraction of these hazardous substances.**

Neutron Activation Techniques

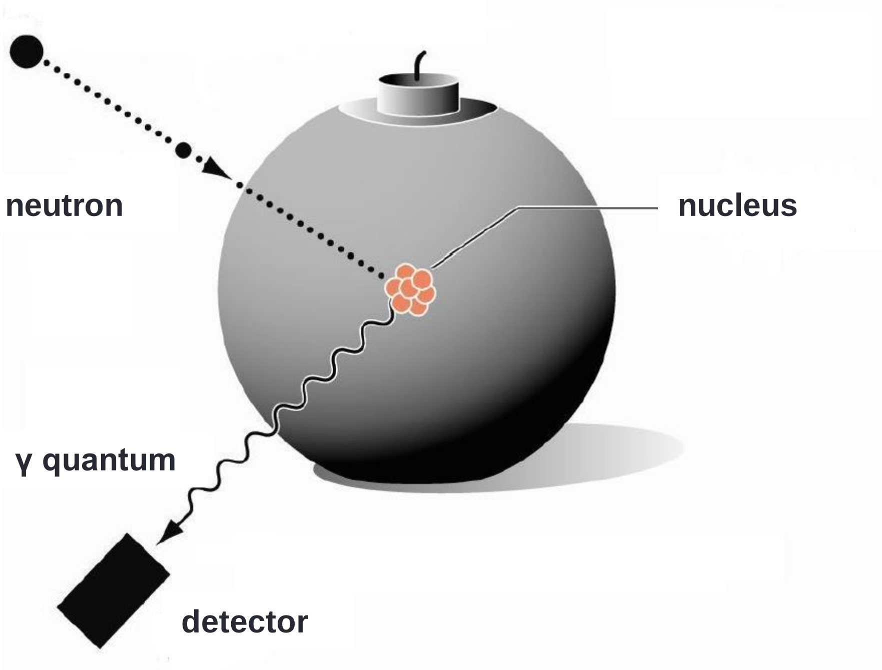
❖ Novel methods of **nondestructive** chemical threat detection based on neutron activation:

Thermal neutron capture (sources, D+Dgenerators)

Neutron inelastic scattering (D+D/**D+T** generator)

D+T → α + n

n + nucleus → nucleus + γ + n



Excited nuclei emit gamma quanta of energy characteristic of the element

Relative content of elements ⇔ Stoichiometry → **Identification**

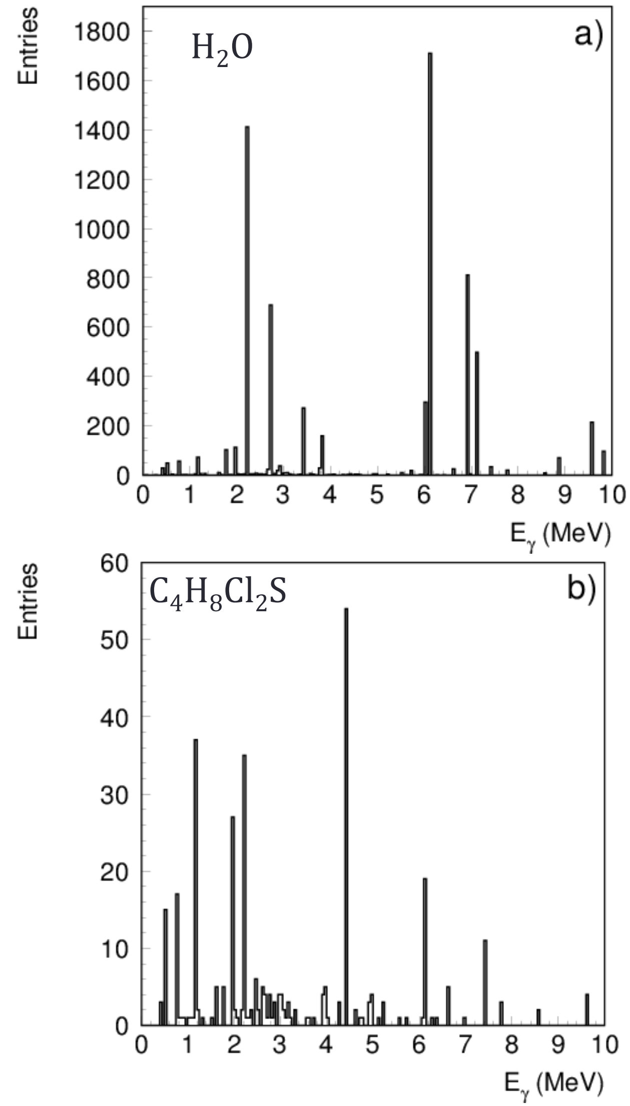
Neutron Activation Techniques

- **Signature:**
  gamma quanta of the following nuclei: **^{12}C** (4.44 MeV), **^{16}O** (6.13 MeV), **^{14}N** (10.83 MeV, 5.27 MeV), **^{37}Cl** (1.17 MeV, 7.79 MeV) **^{32}S** (5.42 MeV) **^{31}P** (1.27 MeV), **^{19}F** (0.11 MeV, 0.197 MeV)
- High penetration allows detection of explosives/ which are hidden in vehicles, buried, etc.

- The use of pulse generators and detection of correlated α particles allows to measure the neutron time of flight ⇔ tomographical picture of the chemical composition of the substance

<u>**Drawbacks:**</u>

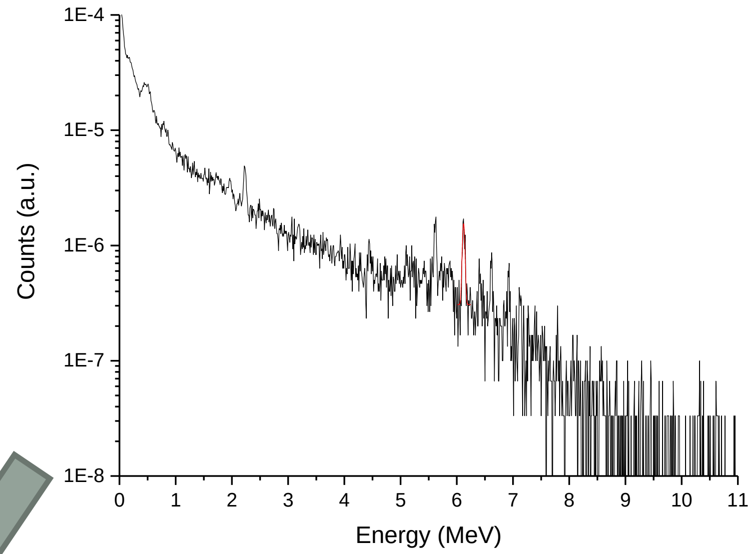
- Small cross sections for some of the elements
- Decreased mobility due to detector cooling
- High neutron flux needed
- Insensitivity to the structure of molecule
- **High neutron attenuation in water**
- **High background from oxygen and nitrogen**



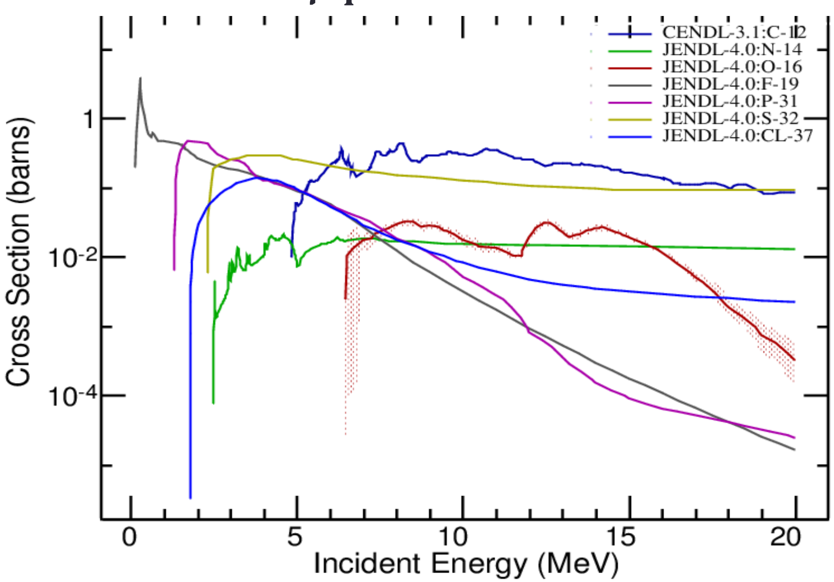
Neutron Activation Techniques

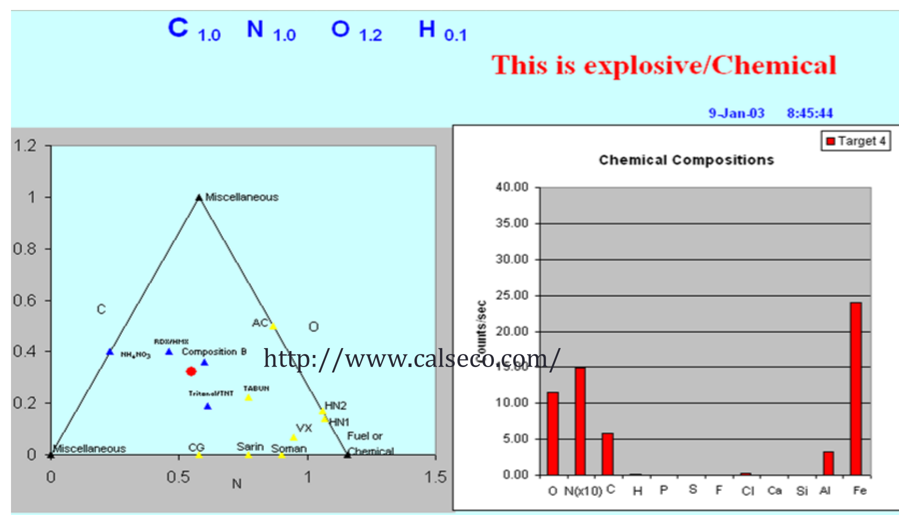
http://www.calseco.com/

γ quanta detection



Data analysis





http://www.calseco.com/

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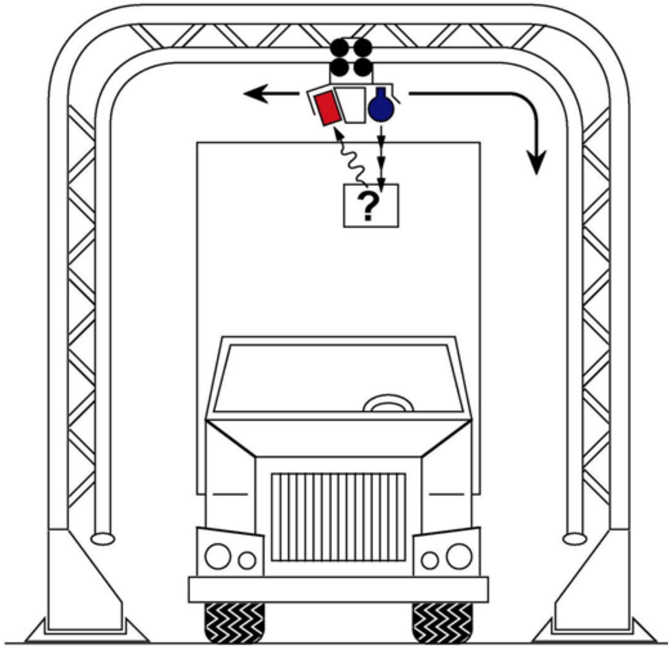
Comparison with database of known substances & identification

Practical applications



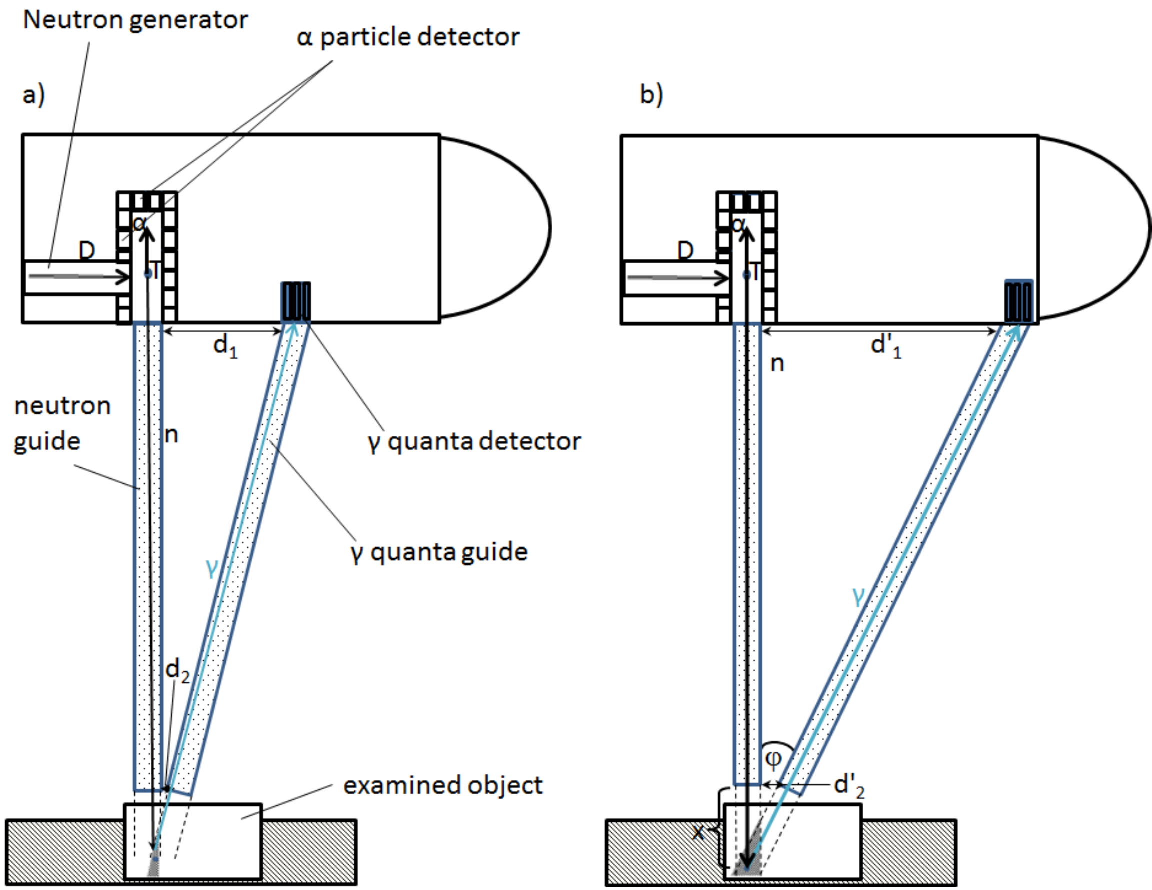
Practical applications

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

http://www.uncoss-project.org/

The SABAT project (Stochiometry 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
- ❖ Changeable position, length and orientation of guides
- ❖ Position sensitive detector (**scintillator**)



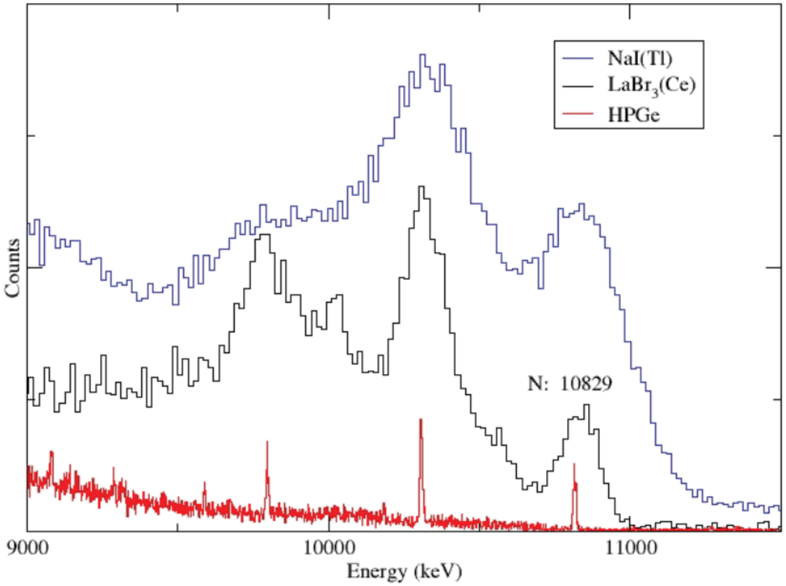
- ❖ Depth of neutron interaction determined from the time difference between neutron and γ quantum registration times:

$$x = \left(\Delta t + \frac{l_\alpha}{v_\alpha} - \frac{l_n}{v_n} - \frac{l_\gamma}{c} \right) \frac{c v_n \cos\varphi}{c \cos\varphi + v_n}$$

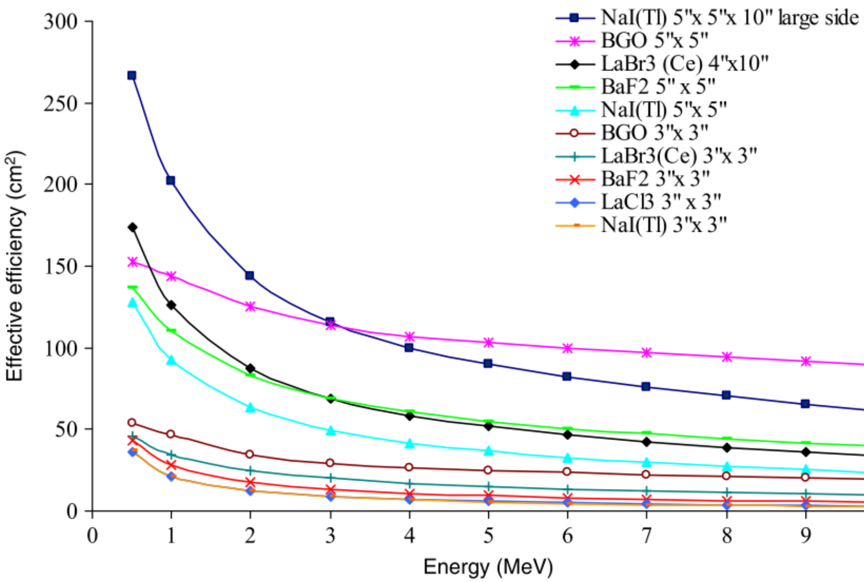
Status of the project: Basic geometry simulations

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

	BGO	NaI:Tl	$LaCl_3$:Ce	$LaBr_3$Ce
Average Z	28	**32**	28	**41**
Density [g/cm³]	7.1	**3.7**	3.9	**5.3**
Energy resolution (@662 keV) [%]	12	**7**	3.3	**2.8**



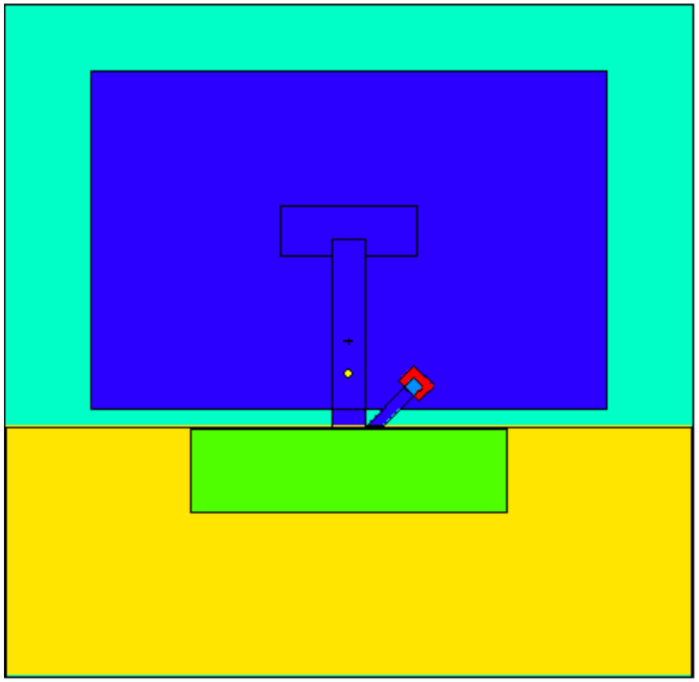
IEEE Nuclear Science Symposium,San Diego, CA,10/29/2006,11/04/2006

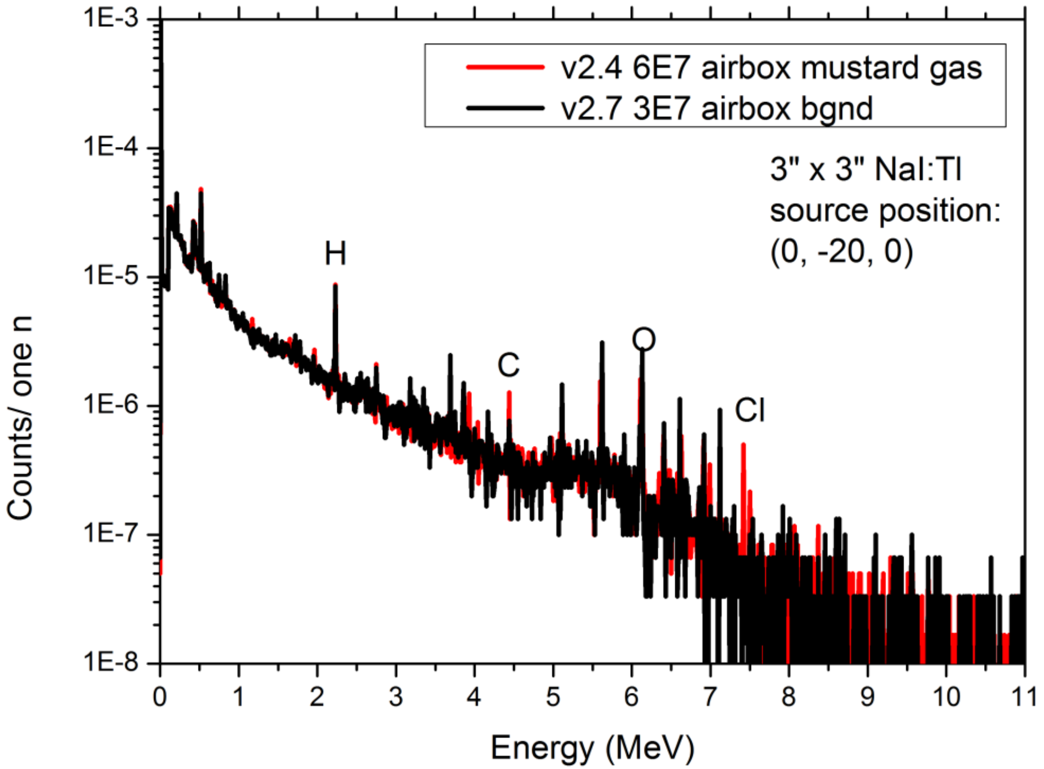


C. Elon et al..NIMA 619 (2010) 234–239

Status of the project: Basic geometry simulations

- ❖ Simulations with MCNPX, so far without alpha tagging and TOF measurement, $3 \cdot 10^7$ neutrons (< 0.3 s of interrogation)
- ❖ NaI:Tl 3" x 3"x3” detector with 5 cm led shield inside a „drone” with dimensions 192 x 192 x 70 cm^3 filled with air.
- ❖ Neutron generator at the lower face of the carrier connected to a guide with cross-section of 20x20 cm^2.
- ❖ 100 x 100 x 40 cm^3 container with mustard gas





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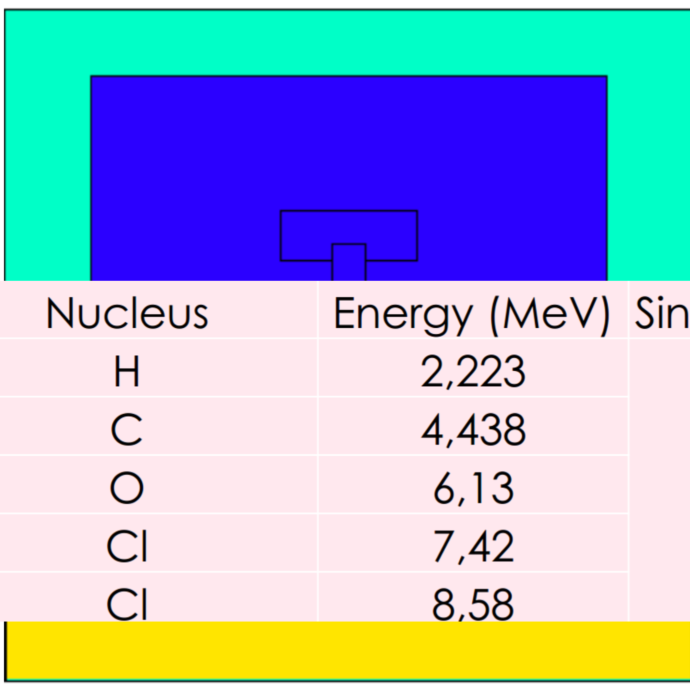
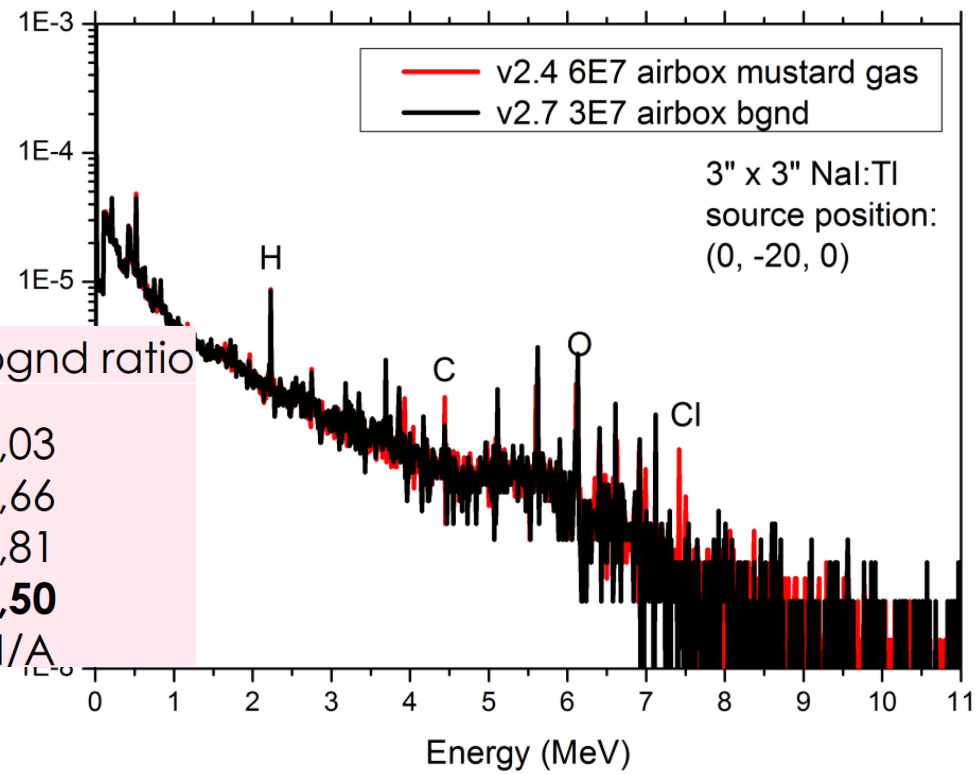
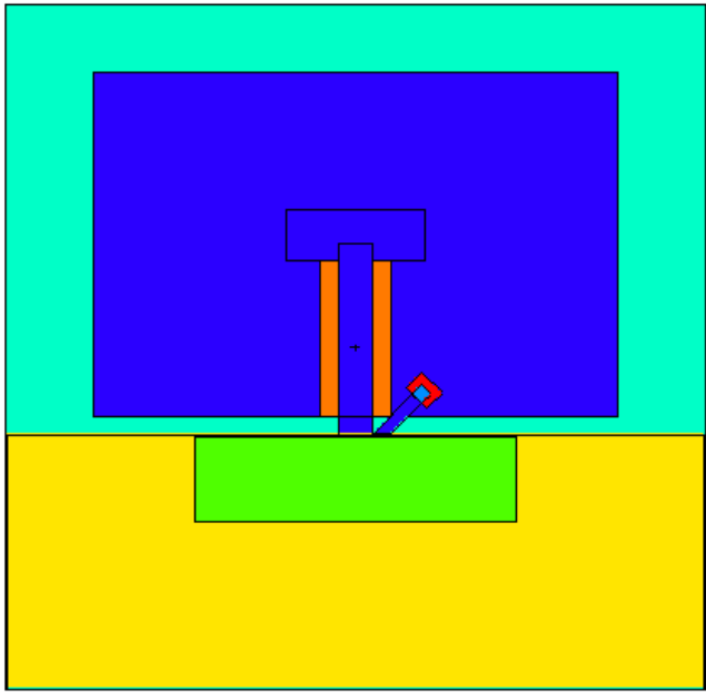


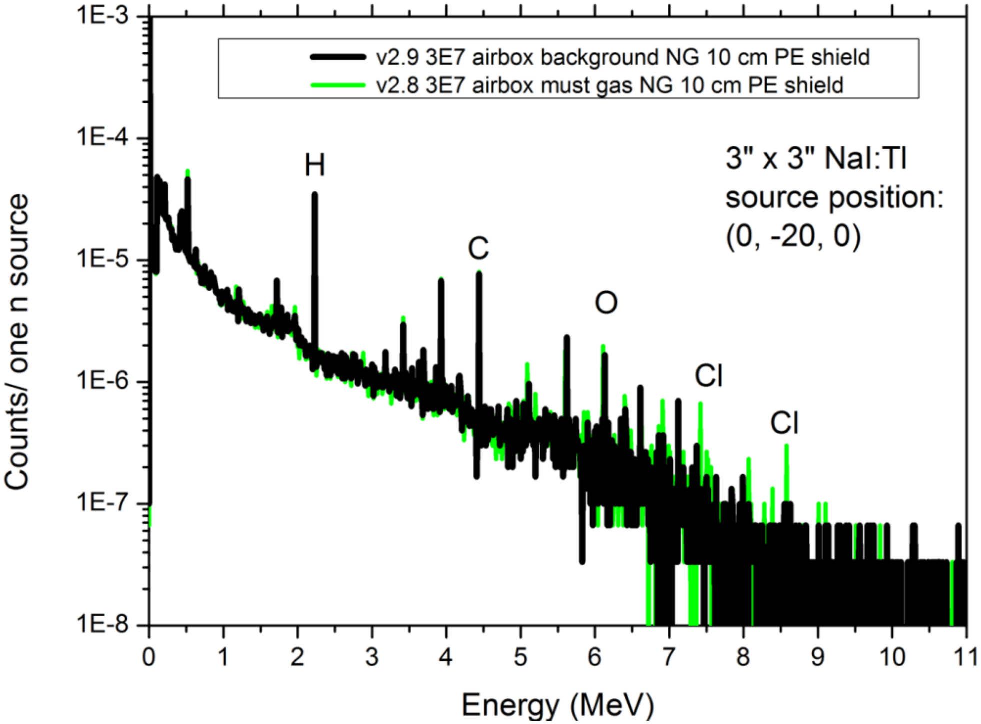
Nucleus	Energy (MeV)	Singal/bgnd ratio
H	2,223	1,03
C	4,438	1,66
O	6,13	0,81
Cl	7,42	**7,50**
Cl	8,58	N/A



Status of the project: Basic geometry simulations

❖ Playing with neutron shielding (polyethylen + led)

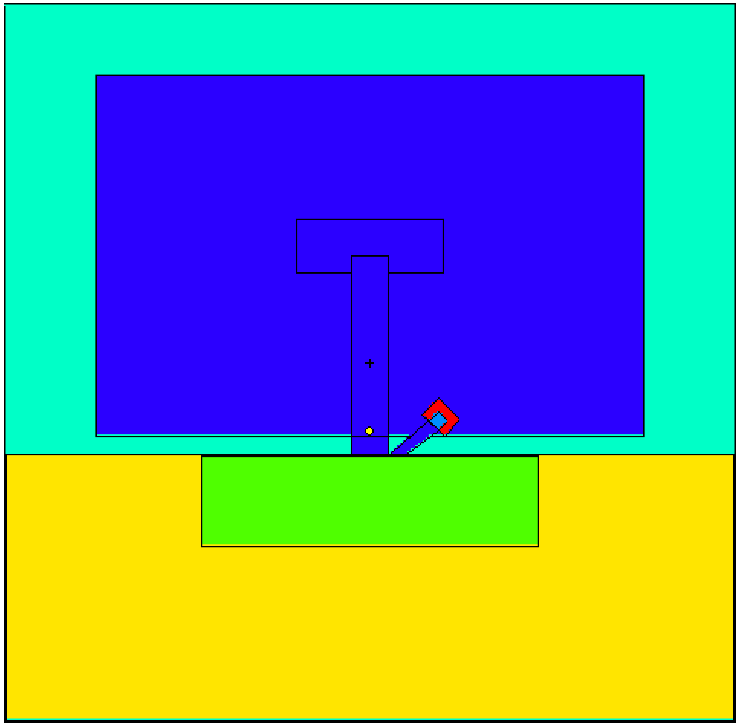


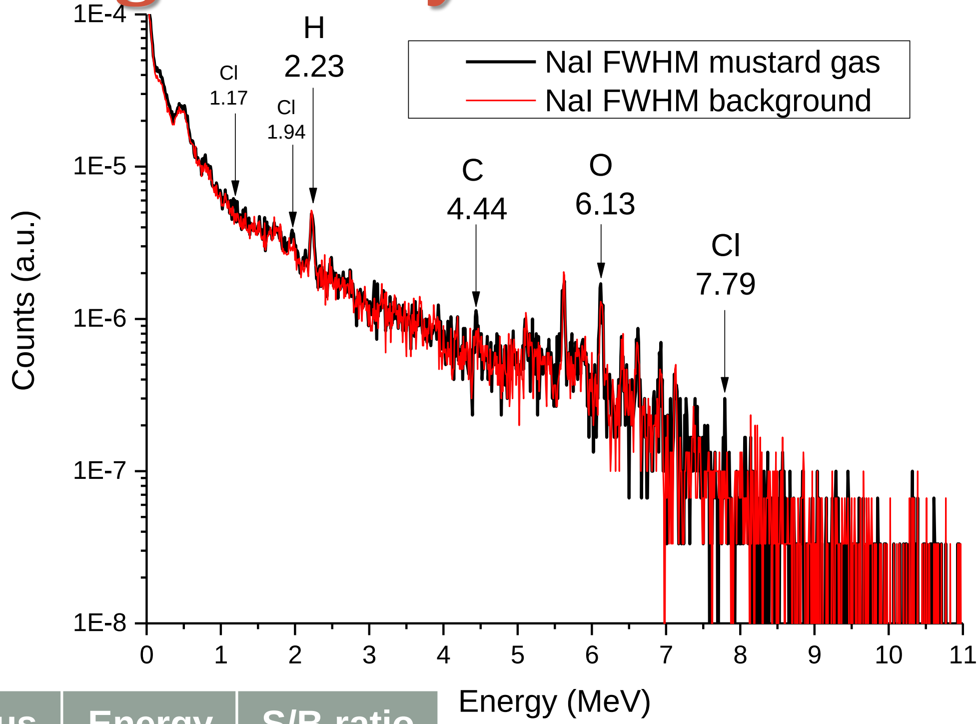


Nucleus	Energy (MeV)	Singal/bgnd ratio
H	2,223	0,90
C	4,438	1,04
O	6,13	1,35
Cl	7,42	2,22
Cl	8,58	3,00

Status of the project: Basic geometry simulations

❖ Best geometry so far

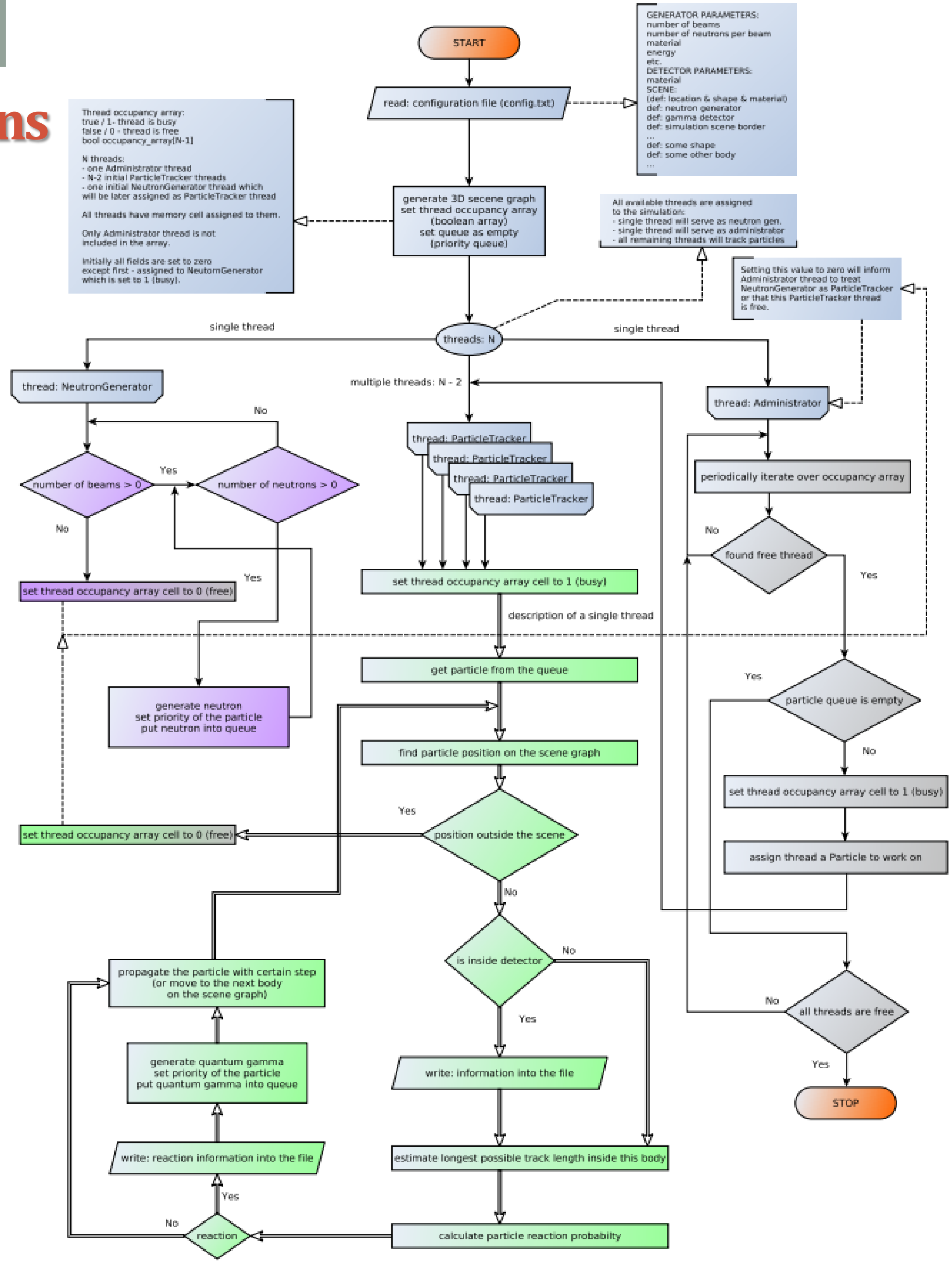




Nucleus	Energy	S/B ratio
Cl	1.17	1.23
Cl	1.94	1.13
H	2.23	0.95
C	4.44	1.29
O	6.13	0.92
Cl	7.79	3
S	5.42	N/A

SABAT Monte Carlo simulations

- **Fast independent simulations devoted only to the NAA applications**
- Open source code (C++ as default programming language, standard version C++11)
- Target OS: Linux (Debian or Red Hat based)
- Multiple cores/threads (Open MPI standard & library)
- Parallel computing
- Physics: ENDF/ENSDF libraries used
- Database : SQLite3
- Relational DataBase Management System, most tables in the second normal or third normal form (2NF & 3NF)
- **Novel method of geometry definition and particle tracking based on hypergraphs**

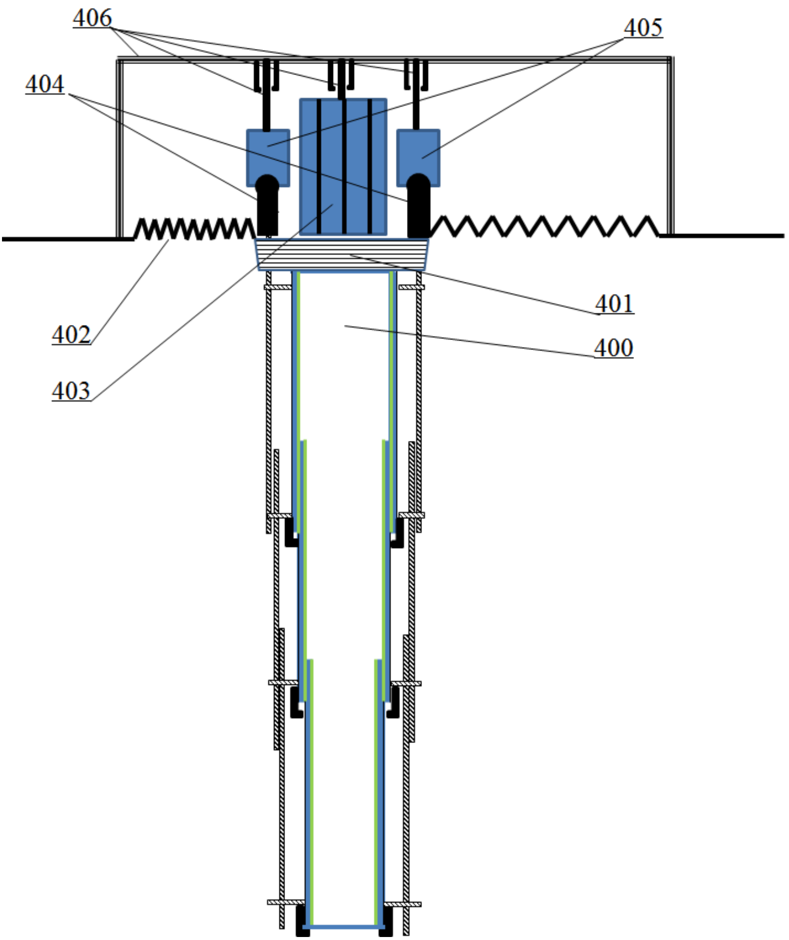


Summary

- The chemical munitions sunk in seas constitute a very serious threat for environment and people
- Methods of detection used so far are not efficient enough to detect all contaminated sea areas
- Promising improvement: neutron activation techniques used on a submarine
- Sensitivity limited by huge background from water
- We expect great noise reduction requiring the coincident detection of the α particle generated together with neutron and taking into account the Time Of Flight measurement
- Design of the prototype of such device was started in the Institute of Physics of the Jagiellonian University
- The SABAT project was founded by NCBR in January 2017
- Construction of the first prototype scheldued for 2019

Goya, *Witches sabbath*

Thank You
for attention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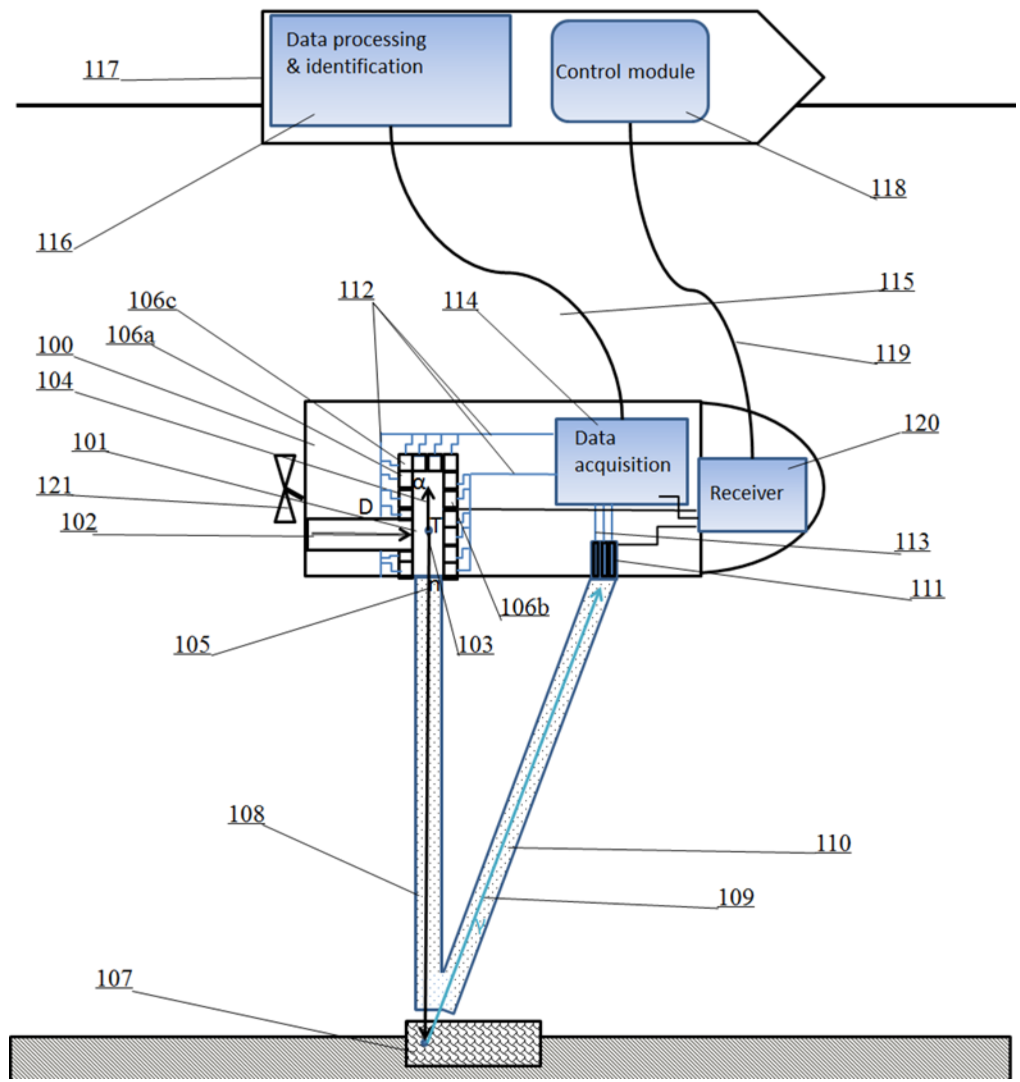
Data processing
& identification
Control module
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Data
acquisition
Receiver
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Place of interaction

(L substances with N_l atoms in molecule)

$$P(x) = 1 - exp(-\mu_{tot}x) \Leftrightarrow x = -\frac{ln(1-F(x))}{\mu_{tot}}; F(x) \in [0,1)$$

(F ≡ Cumulative distribution function of x pdf generated with constant probability)

$$\mu_{tot} = \sum_{i=1}^{N} K_i \sigma_i(E_{neut});$$

$$\left(k_{il} = \frac{S_i}{\sum_{j=1}^{N_l} S_j} \frac{\rho_l N_A}{\sum_{j=1}^{N_l} S_j M_j}; K_i = \sum_{l=1}^{L} k_{il} u_{Vl} \text{ or } K_i = \sum_{l=1}^{L} k_{il} \frac{u_{ml}}{\rho_l \sum_{i=1}^{L} \frac{u_{mi}}{\rho_i}} \right)$$

k_{il} – concentration of i^{th} atom in l^{th} substance

S_i – i^{th} stochiometric coeficient (number of i^{th} atoms in molecule [**DB**]

M_j – molar mass of j^{th} element [**DB**]

ρ_l – density of l^{th} substance [**DB**]

u_{Vl} and u_{Ml} – volume and mass fraction of l^{th} substance, respectively [**CF**]

$\sigma_i(E_{neut})$ – total cross section [**MT = 1**] for interaction with i^{th} element [**DB**]

Element

$$P(i) = \frac{K_i \sigma_i(E_{neut})}{\sum_{i=1}^{N} K_i \sigma_i(E_{neut})}$$

$x < x_{max}$

neutron propagated to x_{max}

Elastic scatering [MT=2]

$E'_{neut} = E_{neut}$

[**DB**] neutron angular distibution ⇒ new neutron direction

Process

(M processes chosen by user in the Config File)

$$P(p) = \frac{\sigma_p(E_{neut})}{\sum_{i=1}^{M} \sigma_i(E_{neut})} \text{ or } P(p) = \frac{\sigma_p(E_{neut})}{\sigma_{tot}(E_{neut})}$$

σ_i – cross section for the process i [**DB**]

Fission

$n{+}A \to A' + A''$ **[MT=19]** (total neutron energy deposition)

$n{+}A \to n' + A' + A''$ **[MT=20]**

$n{+}A \to 2n' + A' + A''$ **[MT=21]**

$n{+}A \to 3n' + A' + A''$ **[MT=38]**

Neutron(s) energies⇐[**DB**]

[**DB**] neutron angular distibution ⇒ new netron direction

Leading to the nuclei excitation

$n + A \to n' + A'^{*} \to n' + A' + \gamma$ **[MT=51-91]**

$n{+}A \to p + A'^{*} \to p + A' + \gamma$ **[MT=601-649]**

$n{+}A \to d + A'^{*} \to d + A' + \gamma$ **[MT=651-699]**

$n{+}A \to T + A'^{*} \to T + A' + \gamma$ **[MT=701-749]**

$n{+}A \to {}^3He + A'^{*} \to {}^3He + A' + \gamma$ **[MT=751-749]**

$n{+}A \to \alpha + A'^{*} \to \alpha + A' + \gamma$ **[MT=801-849]**

Radiative Capture: $n + A \to A'^{*} \to A'\gamma$ **[MT=102]**

Excited level

(Z levels chosen by user in the Config File)

$$P(e) = \frac{\sigma_{ep}(E_{neut})}{\sum_{i=1}^{Z} \sigma_{ip}(E_{neut})}$$

σ_i – cross section for excitiation of level i [**DB**]

List of $\gamma's$ [**DB**] or sequensional calculations of $\gamma's$ energies ⇐ levels energies **[DB]**

$$E'_{particle} = \frac{(E_{neut} + M_A)^2 - M^2{}_{A'} + m^2{}_{particle}}{2(E_{neut} + M_A)} - \sum_{i=1}^{N} E_{\gamma i}$$

[DB] particle angular distibution ⇒ particle direction

N gamma quanta with energy E_γ **[DB]** and direction ⇐ γ angular distribution **[DB]** (usually homogeneous)

M_A / $M_{A'}$, $m_{particle}$ – mass of initial/final nuclei and final particle, respectively **[DB]**

Leading to one particle in the final state

$n{+}A \to p + A'$ **[MT=600]**

$n{+}A \to d + A'$ **[MT=650]**

$n{+}A \to T + A'$ **[MT=700]**

$n{+}A \to {}^3He + A'$ **[MT=750]**

$n{+}A \to \alpha + A'$ **[MT=800]**

$$E'_{particle} = \frac{(E_{neut} + M_A)^2 - M^2{}_{A'} + m^2{}_{particle}}{2(E_{neut} + M_A)}$$

[DB] particle angular distibution ⇒ particle direction

M_A / $M_{A'}$, m_p – mass of initial/final nuclei and final particle, respectively **[DB]**

Leading to more particles in the final state

$n{+}A \to 2n + A'$ **[MT=16]**

$n{+}A \to 2n + A' + \gamma$ **[MT=876]**

$n{+}A \to n + \alpha + A'$ **[MT=22]**

$n{+}A \to n + p + A'$ **[MT=28]**

$n{+}A \to n + d + A'$ **[MT=32]**

$n{+}A \to T + n + A'$ **[MT=33]**

$n{+}A \to {}^3He + n + A'$ **[MT=34]**

$n{+}A \to 2\alpha + A'$ **[MT=108]**

$n{+}A \to 2p + A'$ **[MT=111]**

$n{+}A \to \alpha + p + A'$ **[MT=112]**

$n{+}A \to d + p + A'$ **[MT=115]**

$n{+}A \to T + p + A'$ **[MT=116]**

$n{+}A \to \alpha + d + A'$ **[MT=117]**

$n{+}A \to 3n + A'$ **[MT=17]**

$n{+}A \to n + 2\alpha + A'$ **[MT=29]**

$n{+}A \to 2n + p + A'$ **[MT=41]**

$n{+}A \to n + 2p + A'$ **[MT=44]**

$n{+}A \to p + \alpha + n + A'$ **[MT=45]**

$n{+}A \to T + 2\alpha + A'$ **[MT=113]**

$n{+}A \to 4n + A'$ **[MT=37]**

$n{+}A \to 3n + p + A'$ **[MT=42]**

$n{+}A \to n + 3\alpha + A'$ **[MT=28]**

$n{+}A \to 3n + \alpha + A'$ **[MT=25]**

particle directions and energies have to be generated according to the phace space for M=1...4 particles in the final state (e.g. GENBOD)

Other potentially useful information

Neutron absorption

[MT=27; sum of MT=18 and MT=102 through MT=117]

Neutron disappearance

[MT=101; sum of MT=102-117]