800 ANNI 1222 • 2022

Università degli Studi di Padova

INFN Istituto Nazionale di Fisica Nucleare

Neutron Technique in civil security applications

WHO I AM

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PADOVA PERSONNEL

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- Felix Eduardo Pino Andrades (UniPD–INFN)
- Luca Stevanato (UniPD –INFN)

KNOW HOW AND EXPERTISE

- Radiation detectors development and characterization;
- Neutron and Gamma detection and discrimination:
  detectors and software;
- Monte Carlo simulation:
  Geant4, MCNP and Penelope;
- Data Acquisition Systems:
  Middleware and on-line analysis

Civil Security

- The fight against terrorism and crime:

  […]New technologies to detect weapons and explosives

  New approaches to the prevention and prosecution of financial crimes (e.g. money laundering)

  Optimizing operations tactics and technologies used by police forces, specialist authorities, fire brigades and rescue services to recognize, assess and control emergency situations caused by the deliberate release of CBRN substances […]

[Research for Civil Security 2018–2023A Federal Government Framework Programme]

Previous projects: MODES_SNM (FP7 SEC-2011.1.5-1) 2012-2104

Van-mounted detection system for radioactive and Special Nuclear Materials (SNM).

The MODES_SNM system complies with the IAEA requirements for Portable Radiation Scanners (PRS).

Previous projects: TAWARA_RTM (FP7 SEC-2012.1.5-2) 2013-2016

Complete platform to monitor the **radioactivity content of tap water**, including:

- Early Alarm Detector (EAD);
- Fast Real-Time Monitor systems;
- Spectroscopic system;
- ICT supporting chemical and biological sensors.

Previous projects: C-BORD (H2020 EU3.7 BES-09-2014) 2015-2018

Framework for the **Non-Intrusive Inspection (NII) of containerised freight**. Includes: Improved X-rays, Target Neutron Interrogation, Photofission, Sniffer and improved Passive Detection.

We were leader of **Tagged Neutron Inspection System**, for detection of explosives and illicit drugs, TRL6 level.

NON DESTRUCTIVE ANALYSIS

NON DESTRUCTIVE ANALYSIS

- Non-destructive analysis (NDA) of materials is a well-known technique applied in several fields.
- Neutron interrogation based methods of NDA are well established techniques employed in the field of bulk material analysis.

Why neutrons?

- Neutron as a neutral particle can penetrate deeply even in dense material.
- Neutrons interact only with nuclei
- When a neutron does interact with a nuclide, it is affected in a unique way that depends on the incident energy of the neutron and the species of the target nuclide.

Neutron Based Technique

- Elastic and inelastic neutron scattering and neutron capture reactions as well as its combination are used for the development of the variety of Neutron Based techniques.

Neutron Based Technique

- Neutron interrogation techniques generally rely on bombarding the nuclei in the interrogated object with neutrons of particular energy or energies, causing them to emit characteristic γ-rays or alter the energy or the direction of the interrogating neutrons.

What are neutrons used for?

https://www.ill.eu/science-technology/the-neutron/what-are-neutrons-used-for/

What are neutrons used for? (I)

- **Condensed-matter physics, materials science and chemistry**

  Examination of the structure of new materials

  Storing of hydrogen in metals (renewable energy sources).

  Analysis of parameters in polymers.

  Colloid research in pharmaceuticals, food industry and medicine.

What are neutrons used for? (II)

- **Biosciences**

  Biological materials, naturally rich in hydrogen and other light elements, are ideal samples for analysis with neutrons.

  - Cell Membranes
  - Proteins
  - Virus Investigations
  - Photosynthesis in Plants

What are neutrons used for? (III)

- **Engineering sciences**

  Since neutron diffraction is non-destructive, it is ideal for the analysis of different technical phenomena in materials.

  - Visualization of residual stress in materials (example: railway rails).
  - Hardening and corrosion phenomena in concrete.
  - Inhomogeneity and trace elements in materials.

What are neutrons used for? (III)

- **Civil Security**

  Second line of inspection to detect

  - Explosives
  - Chemical agents
  - Contraband cigarettes
  - Verify the X-ray alarm

THE GENERAL CONCEPT

The General Concept

The core idea is to use:

- Neutron sources
- Different neutron interactions
- Detectors for gamma/neutron

Neutron Interactions

Neutrons interactions depends on energies:

- Neutrons are uncharged particles:
  - No interaction with atomic electrons of material
  - Interaction with the nuclei of these atoms
- The nuclear force, leading to these interactions, is very short ranged
  - neutrons have to pass close to a nucleus to be able to interact ≈ 10-13 cm (nucleus radius)
- Because of small size of the nucleus in relation to the atom, neutrons have low probability of interaction
  - long travelling distances in matter

See TextBook Krane, Segre', …

NEUTRON SOURCES

Neutron Sources

Some radioisotopes, nuclear reactor, or accelerator-based devices can be used as neutron sources.

Now…

- https://drive.google.com/open?id=1qVMz8HjBDtGX9HNNeRVKhhT66-55s-Iu

- Split into small groups
- Each person in the group read a different pdf file (Neutron source, ..)(5 min)
- Each person reports to the rest of the group (5 min/each)

Neutrons radioisotope sources

- Radioisotopes used as the neutron sources include 252Cf, 239Pu, 241Am, and others.
- Radioisotope sources of neutrons are cheaper and smaller then neutron generators but neutron yield of these sources is decaying with time and typically limited to a total intensity of 10^7n/s.
- Also radioactive sources capable of producing high neutron flux contain hazardous quantities of radiation requiring many safety considerations.

Neutrons radioisotope sources

The most common sources of neutrons are:

- (α,n) reaction neutron source
- Spontaneous fission neutron source

Spontaneous fission neutron source

- 252Cf and all other spontaneous fission neutron sources are produced by irradiating uranium or another transurani celement in a nuclear reactor; neutrons are absorbed in the starting material and its subsequent reaction products, transmuting the starting material into the SF isotope.
- When purchased new typical 252Cf neutron sources emit between 1×10^7 to 1×10^9 neutrons per second but with a half life of 2.6 years

252-Californium

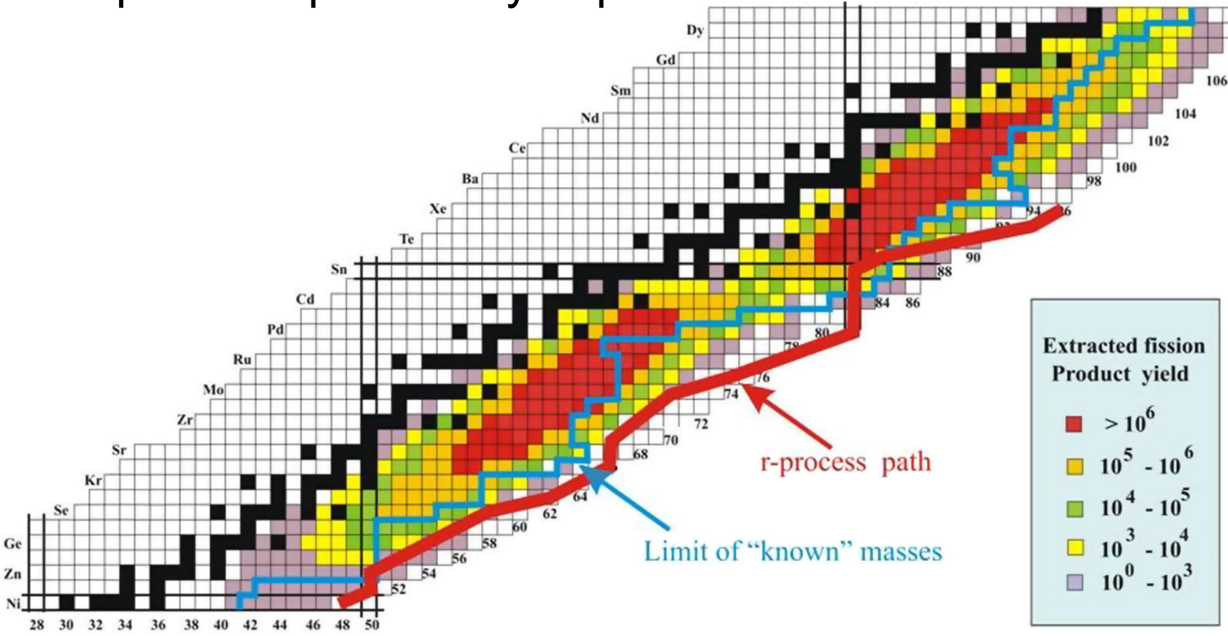
- Total Half-live: 2.7 years
- Half-live for alpha decay: 2.7 years (Eα=6.117 MeV)
- Half-live for spontaneous fission: 85.5 years
- Specific activity: 500 µCi / µg (6.2 x 105 fission / µg)
- Neutron multiplicity: 3.7 (<En>=2.35 MeV)
- Gamma multiplicity: about 10 (80% with energy E<1. MeV)

252-Californium

- Sealed sources, double stainless steel container.
- Typical geometry (Savannah River type) : right cylinder, 3.7 cm long, 0.92 cm dia.
- The 252Cf is contained in a ceramic pellet (1 mm3 volume) placed inside the stainless steel container.

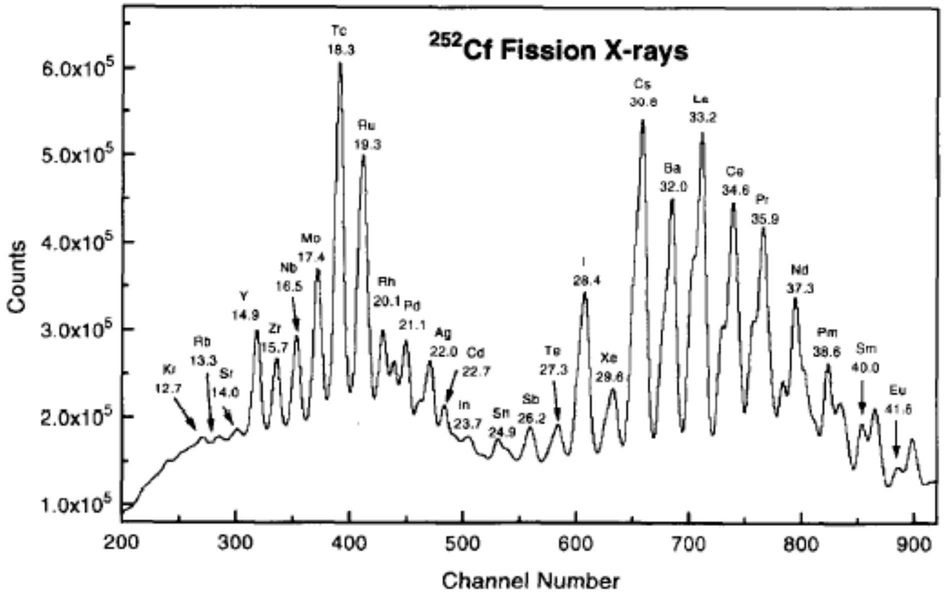
252Cf fission fragments mass distribution

The distribution of fission fragments from 252Cf [2] covers a wide region of the neutron-rich side and populates some of the most important nuclei, such as 132Sn and 100–106Zr, for nuclear physics studies. In addition the mass distribution of 252Cf is quite complimentary to proton or neutron-induced fission of uranium



https://doi.org/10.1016/j.nimb.2007.04.132

X-rays from fission fragments

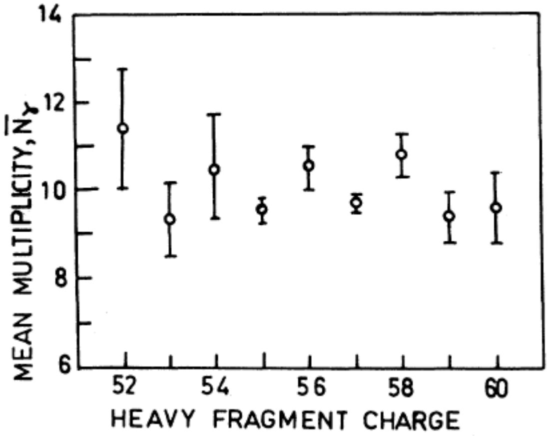


- Total X-ray projection spectrum for 252 Cf as measured with the LEPS detectors. Peaks marked with elemental symbol and energy in keV are K_α X-ray transitions. Some of the smaller peaks in the large Z, X-ray region are K_β lines.

https://doi.org/10.1016/0168-9002(95)00072-0

Gamma ray from 252-Cf

- Mean Gamma Ray multiplicity as a function of heavy-fragment charge.



Prompt gamma-ray multiplicity distributions in spontaneous fission of 252Cf
Raghav Varma, G. K. Mehta, R. K. Choudhury, S. S. Kapoor, B. K. Nayak, and V. S. Ramamurthy
Phys. Rev. C 43, 1850 – Published 1 April 1991

Neutron Emission from 252-Cf

PHYSICAL REVIEW VOLUME 126, NUMBER 6 JUNE 15, 1962

Velocity and Angular Distributions of Prompt Neutrons from Spontaneous Fission of Cf^{252}

Harry R. Bowman, Stanley G. Thompson, J. C. D. Milton, and Wladyslaw J. Swiatecki
Lawrence Radiation Laboratory, University of California, Berkeley, California

(Received January 15, 1962)

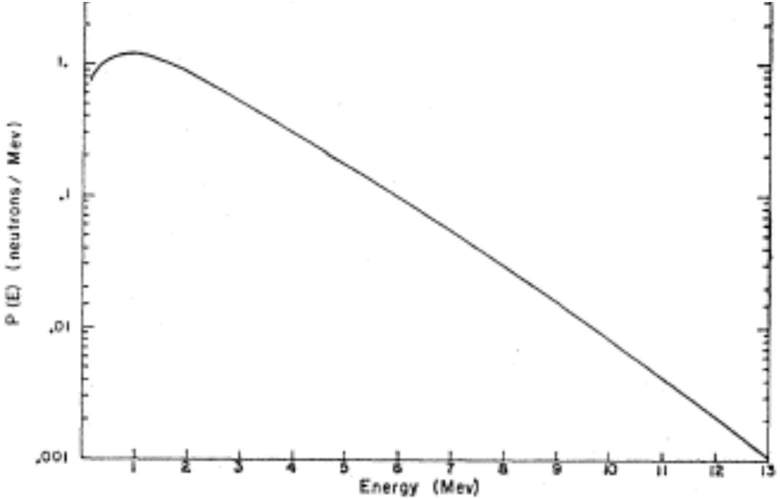
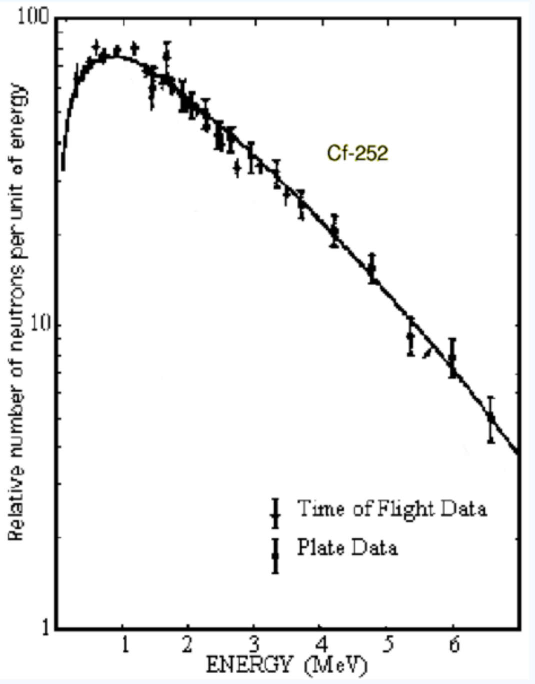


Fig. 14. Energy spectrum in the laboratory system for Cf^{252}. The spectrum is calculated from the parameters of line 1, Table VI, and consequently sums to 3.67 neutrons per fission.

Neutron Energy Spectrum

$$\frac{dN}{dE} = \sqrt{E}\exp\left(\frac{-E}{T}\right)$$

T = 1.3 MeV



(α,n) reaction neutron source

- Radioisotopes which decay with alpha particles packed in a low-Z elemental matrix:
- Neutrons are produced when alpha particles impinge upon any of several low atomic weight isotopes including isotopes of beryllium, carbon and oxygen.
- This nuclear reaction can be used to construct a neutron source by intermixing a radioisotope that emits alpha particles such as radium or polonium with a low atomic weight isotope, usually in the form of a mixture of powders of the two materials.
- Typical emission rates for alpha reaction neutron sources range from 1×10^6 to 1×10^8 neutrons per second.

Be(α,n) neutron source

NEUTRON SOURCES 23

TABLE 1-6 Characteristics of Be(α, n) Neutron Sources

Source	Half-Life	E_α (MeV)	Neutron Yield per 10^6 Primary Alpha Particles: Calculated	Neutron Yield per 10^6 Primary Alpha Particles: Experimental	Percent Yield with $E_n < 1.5$ MeV: Calculated	Percent Yield with $E_n < 1.5$ MeV: Experimental
^{239}Pu/Be	24000 y	5.14	65	57	11	9–33
^{210}Po/Be	138 d	5.30	73	69	13	12
^{238}Pu/Be	87.4 y	5.48	79[a]	—	—	—
^{241}Am/Be	433 y	5.48	82	70	14	15–23
^{244}Cm/Be	18 y	5.79	100[b]	—	18	29
^{242}Cm/Be	162 d	6.10	118	106	22	26
^{226}Ra/Be + daughters	1602 y	Multiple	502	—	26	33–38
^{227}Ac/Be + daughters	21.6 y	Multiple	702	—	28	38

[a] From Anderson and Hertz.[14] All other data as calculated or cited in Geiger and Van der Zwan.[15]
[b] Does not include a 4% contribution from spontaneous fission of ^{244}Cm.

Am-B and Am-Be neutron energy

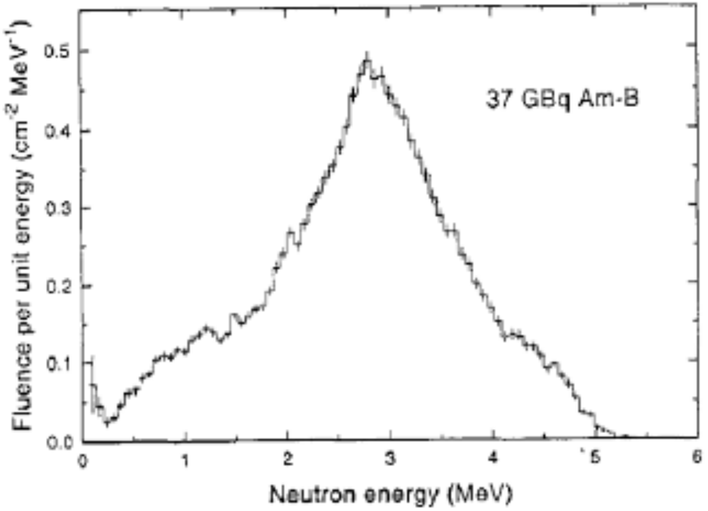


Fig. 7. Measured neutron energy spectrum from the 37 GBq Am–B neutron source normalized to unit fluence, (uncertainties are due to counting statistics only).

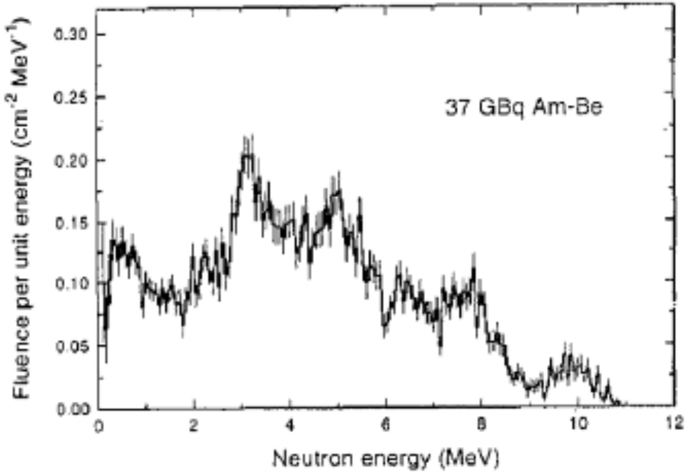


Fig. 5. Measured neutron energy spectrum from the 37 GBq Am–Be neutron source normalized to unit fluence, (uncertainties are due to counting statistics only).

J.W. Marsh et a/ . I Nucl. /nstr . and Meth. in Phys. Res. A 366 (1995) 340-348

Accelerator-based devices

Sealed Portable Neutron Generators

What is an Electronic Neutron Generator?

- A device containing a small linear accelerator (1-5 cm beam length) that produces neutrons as a result of DD or DT fusion by accelerating D and/or T ions into a metal hydride target that is loaded with D and/or T atoms

What is an Electronic Neutron Generator?

- Other types of instruments have also been designed to generate neutrons including inertial electrostatic confinement (IEC) devices and plasma focus devices – however, these have yet to reach commercial maturity due to issues related to complexity, size, cost, operating lifetime, and reliability

What is an Electronic Neutron Generator?

- Neutron generators have several distinct components, in some designs these are separate in others some are integrated together

Neutron Tube	HV Housing	HV Power Supply	Control System
- Ion Source - Gas Reservoir - Accelerating Gap - Ion lens - Target - HV insulator - Vacuum envelope	- Tube mounting - HV insulation - Electrical connections to neutron tube	- HV for acceleration	- Operates device & adjusts performance

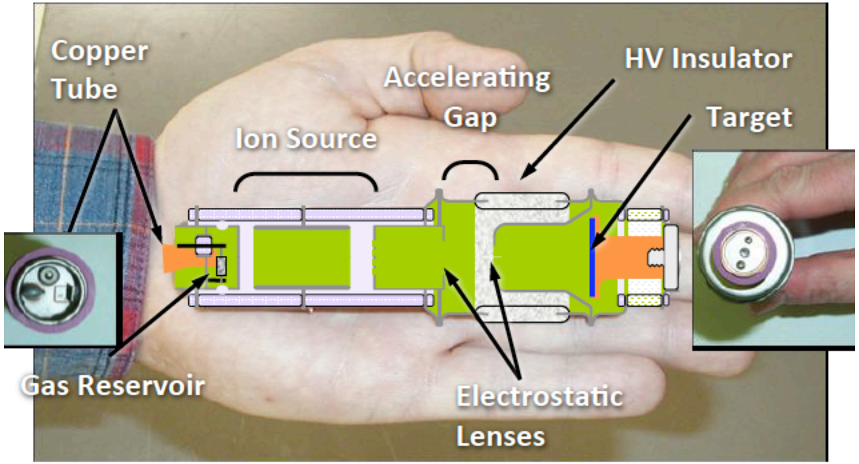
IS Power Supply
- Provides current for ion source

R Power Supply
- Provides current for reservoir

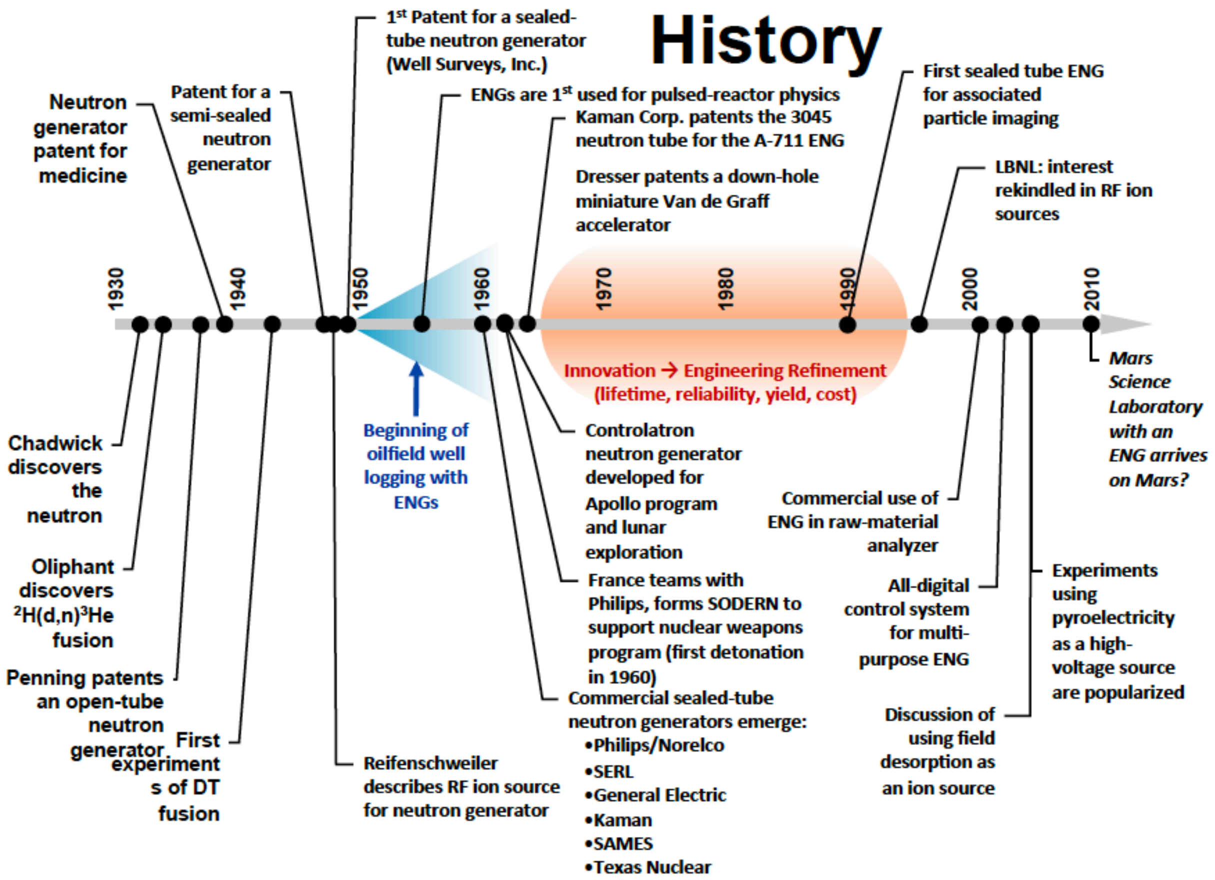
Neutron Tube

Neutron Tube

- Ion Source
- Gas Reservoir
- Accelerating Gap
- Electrostatic lenses
- Target
- HV insulator
- Vacuum envelope



History


History
1930
1940
1950
1960
1970
1980
1990
2000
2010
Neutron generator patent for medicine
Patent for a semi-sealed neutron generator
1st Patent for a sealed-tube neutron generator (Well Surveys, Inc.)
ENGs are 1st used for pulsed-reactor physics
Kaman Corp. patents the 3045 neutron tube for the A-711 ENG
Dresser patents a down-hole miniature Van de Graff accelerator
First sealed tube ENG for associated particle imaging
LBNL: interest rekindled in RF ion sources
Innovation → Engineering Refinement (lifetime, reliability, yield, cost)
Mars Science Laboratory with an ENG arrives on Mars?
Chadwick discovers the neutron
Oliphant discovers 2H(d,n)3He fusion
Penning patents an open-tube neutron generator
First experiments of DT fusion
Beginning of oilfield well logging with ENGs
Reifenschweiler describes RF ion source for neutron generator
Controlatron neutron generator developed for Apollo program and lunar exploration
France teams with Philips, forms SODERN to support nuclear weapons program (first detonation in 1960)
Commercial sealed-tube neutron generators emerge:
•Philips/Norelco
•SERL
•General Electric
•Kaman
•SAMES
•Texas Nuclear
Commercial use of ENG in raw-material analyzer
All-digital control system for multi-purpose ENG
Discussion of using field desorption as an ion source
Experiments using pyroelectricity as a high-voltage source are popularized

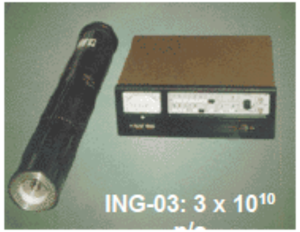
Categories of Neutron generator

ENG Category	Primary Applications	Key Performance Criteria
Logging-While-Drilling (LWD)	Oilfield drilling measurements	Extreme ruggedness and small diameter
Wireline (W)	Oilfield well surveys	Extreme ruggedness and small diameter
Portable (P)	Security, science	Light weight (~ l0 - 15 kg), small overall size, and operational flexibility
General Purpose (GP)	Bulk material analysis, security, medicine, general science	Operational flexibility, no active cooling
Active Cooling (AC)	Bulk and trace material analysis, security, radiation effects testing, general science	Neutron yield
Associated Particle (AP)	Security	Associated particle detector performance, beam spot size (imaging)

Today's Commercial ENGs

ВНИИА

Multiple systems, typical operating lifetimes of ~100 hours



adelphi TECHNOLOGY, INC.

DD-108: 1 x 10^{8} n/s DD
(no representative photo available)

EADS SODERN

Thermo SCIENTIFIC

P 385: 3 x 10^{8} n/s DT (no representative photo available)

Application

- Likely to be the largest industrial market for ENGs (outside the oilfield) over the next 5 years
- Spurred by pressures to avoid and eliminate the use of 252Cf

Examples

- Coal, the use of 14.1 MeV neutrons allows direct measurement of oxygen (energy & BTU)
- Cement
- Mineral ores

See http://www.sodern.com/sites/en/ref/Neutron-elementalanalysis_33.html

THE MOST COMMON TECHNIQUES

Neutron Based Technique

- Prompt Gamma Neutron Activation Analysis (PGNAA)
- Instrumental Neutron Activation Analysis (INAA)
- Associated Particle Imaging Neutron Technique (API)
- Fast Neutron and Gamma Transmission (FNGT)
- Pulsed Fast Neutron Analysis (PFNA)
- Pulsed Fast/Thermal Neutron Analysis(PFTNA)

INAA (INSTRUMENTAL NEUTRON ACTIVATION ANALYSIS) AND PROMPT GAMMA ACTIVATION ANALYSIS (PGNAA)

The radiative neutron capture process

Whenever a nucleus captures a neutron, a compound nucleus is formed. The excitation energy is close to the binding energy, i.e. the kinetic energy of the neutron is negligible (in the MeV range), when irradiating with slow neutrons. This excitation energy is between 6 and 10 MeV for about 80% of the stable nuclei.

The radiative neutron capture process

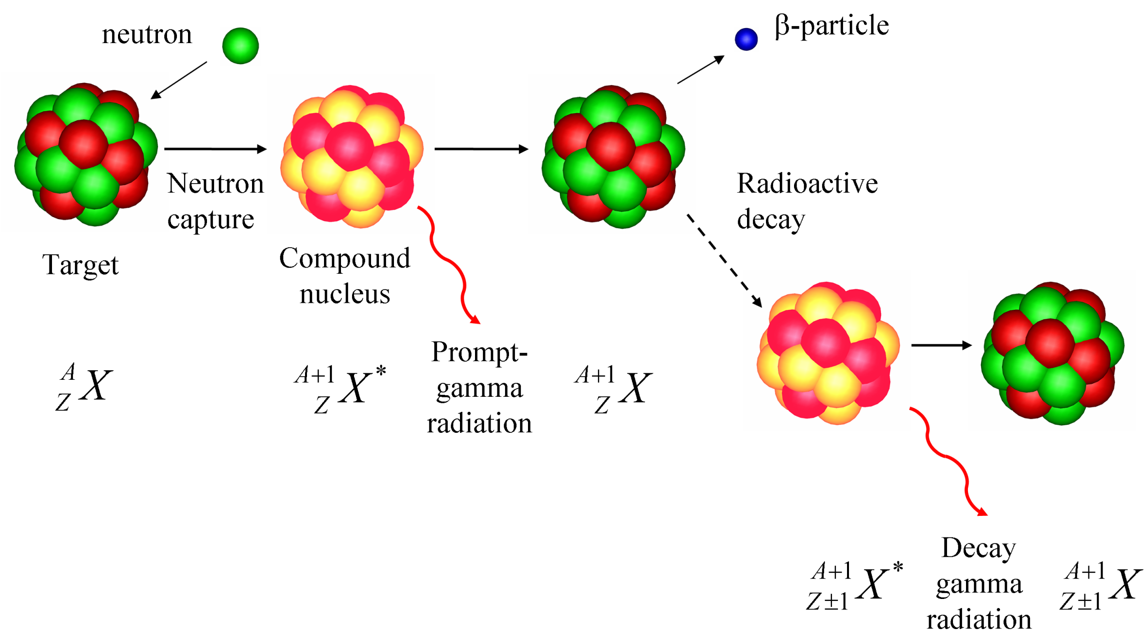
The decay of the compound nucleus takes place in about 10^{-16} s. The nucleus reaches its ground state, typically in 10^{-9} – 10^{-12} s, by emitting 2–4 gamma rays in a cascade. Gamma rays are called prompt, if their decay times following the capture, are much shorter than the resolving time of the detection system, which typically is in the range of 10 ns to 10 μs.

The radiative neutron capture process

Prompt gamma radiation is characteristic, i.e. the energy values of the gamma rays identify the nuclide, and their intensities are proportional to the number of the atoms.

Most nuclides emit hundreds (sometimes several thousands) of different energy prompt gamma-rays. When the ground state reached after the de-excitation is not stable, radioactive decay radiation (typically beta-decays and electron capture followed by gamma-rays) with a given half-life will also be emitted.

Neutron Interactions



INAA (INSTRUMENTAL NEUTRON ACTIVATION ANALYSIS)

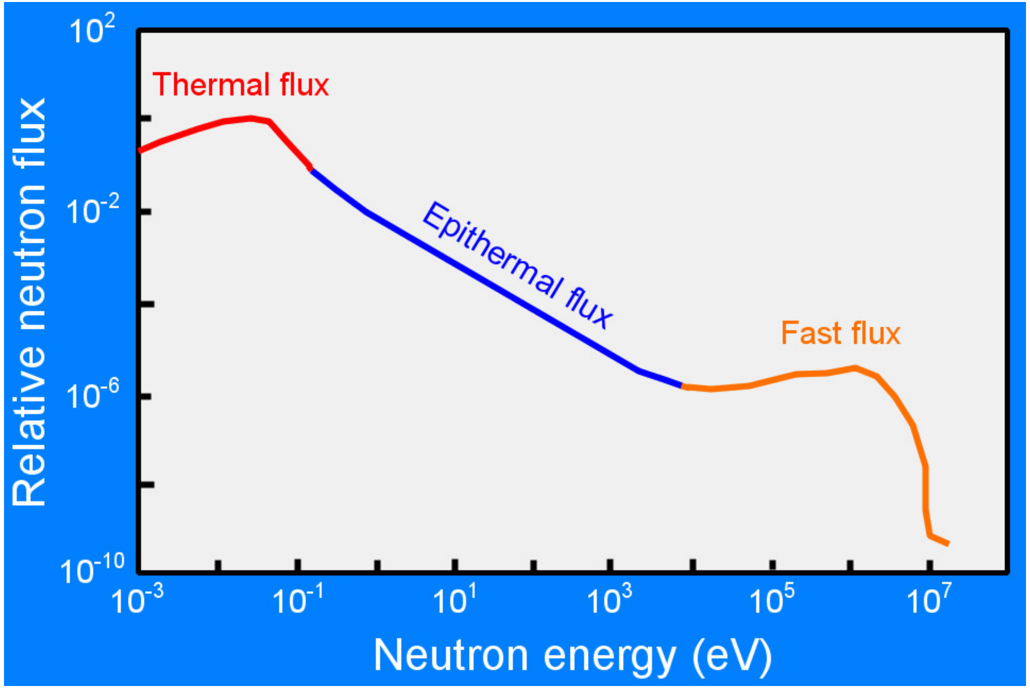
INAA

- Instrumental neutron activation analysis (INAA) is used to determine the concentration of trace and major elements in a variety of matrices.
- A sample is subjected to a neutron flux and radioactive nuclides are produced. As these radioactive nuclides decay, they emit gamma rays whose energies are characteristic for each nuclide.
- Comparison of the intensity of these gamma rays with those emitted by a standard permit a quantitative measure of the concentrations of the various nuclides.

Fundamental Principles of Instrumental Neutron Activation Analysis (INAA)

- The probability of a neutron interacting with a nucleus is a function of the neutron energy. This probability is referred to as the capture cross-section, and each nuclide has its own neutron energy—capture cross-section relationship. For many nuclides, the capture cross-section is greatest for low energy neutrons (referred to as thermal neutrons). Some nuclides have greater capture cross-sections for higher energy neutrons (epithermal neutrons). For routine neutron activation analysis we are generally looking at nuclides that are activated by thermal neutrons.

Neutron energy relative to neutron flux



Now…

- Go to the following link to solve the next information:
- https://www.nndc.bnl.gov/nudat2/

Fundamental Principles of Instrumental Neutron Activation Analysis (INAA)

The n-gamma reaction is the fundamental reaction for neutron activation analysis. For example, consider the following reaction:

$$^{58}Fe + {}^{1}n \rightarrow {}^{59}Fe + Beta^{-} + \text{gamma rays}$$

^{58}Fe is a stable isotope of iron while ^{59}Fe is a radioactive isotope.

With a half life ????

The gamma rays emitted during the decay of the ^{59}Fe nucleus have energies of ??? KeV, and these gamma ray energies are characteristic for this nuclide

INAA

- The activity for a particular radionuclide, at any time t during an irradiation, can be calculated from the following equation

  $A_t = \sigma_{act}\varphi N(1—e^{-\lambda t})$

  where A_t = the activity in number of decays per unit time, σ_{act} = the activation cross-section, φ = the neutron flux (usually given in number of neutrons cm^{-2} s^{-1}), N = the number of parent atoms, λ = the decay constant (number of decays per unit time), and t = the irradiation time.

- The total activity for a particular nuclide is a function of the activation cross-section, the neutron flux, the number of parent atoms, and the irradiation time.
- Note that for any particular radioactive nuclide radioactive decay is occurring during irradiation, hence the total activity is determined by the rate of production minus the rate of decay.
- If the irradiation time is much longer than the half-life of the nuclide, saturation is achieved. What this means is that the rate of production and decay is now in equilibrium and further irradiation will not lead to an increase in activity.

INAA

- After the sample has been activated, the resulting gamma ray energies and intensities are determined using a solid-state detector (usually Ge). Gamma rays passing through the detector generate free-electrons. The number of electrons (current) is related to the energy of the gamma ray.

STRENGHTS INAA

- Can analyze a large number of elements simultaneously
- Very low detection limits for many elements
- Small sample sizes (1—200 mg)
- No chemical preparation
- Non-destructive. The material is available for other analytical techniques

Additionally, compared to many analytical techniques, the instrumentation cost is relatively low. In 2010 it would cost about $50,000 to set-up an INAA laboratory.

LIMITATIONS

- The major limitation is the number of elements that can be analyzed by this technique. Several elements of geological interest, such as Nb, Y and some transition metals, are better determined by other analytical methods.
- For example, more precise Rb, Sr, Y, Nb, and Zr concentrations can be obtained by x-ray fluorescence (XRF). In fact, INAA and XRF are complimentary techniques and rock and mineral chemistries are often determined using both INAA and XRF.
- Also, because there is no chemical pre-separation, the sensitivity of the method is dependent upon the sample matrix.

PROMPT GAMMA ACTIVATION ANALYSIS (PGNAA)

Prompt gamma activation analysis (PGNAA)

- Prompt gamma activation analysis (PGNAA) is a nuclear analytical technique based on the radiative neutron capture, for non-destructive determination of elemental and isotopic compositions.
- The sample is irradiated in a neutron beam and the gamma-rays from the radiative capture are detected. All elements can be analyzed (except helium), without any prior information on the analyte.

Prompt gamma activation analysis (PGNAA)

Contrary to the instrumental neutron activation analysis (INAA), the irradiation and the detection is simultaneous. The energies and intensities of the peaks are independent of the chemical state of the material; hence the analytical result is free of chemical compositions. Both neutrons and gamma-rays are highly penetrating, therefore – in contrast to many instrumental elemental analysis techniques – the average composition of the entire illuminated volume is obtained.

Prompt gamma activation analysis (PGNAA)

- The probability of a reaction is characterized by the cross section. The capture cross section is highly dependent on the neutron energy.
- For slow neutrons the most important energy dependence is the so-called 1/v law. This dependence continues until the first, so-called resonance in the eV – keV range.

Now…

- B-10 is used for the PGNNA
- Go to the https://www-nds.iaea.org/pgaa/pgaa7/index.html

Now…

Become an expert

- https://nucleus.iaea.org/Pages/pgaa-iaea.aspx
- https://www.nndc.bnl.gov/

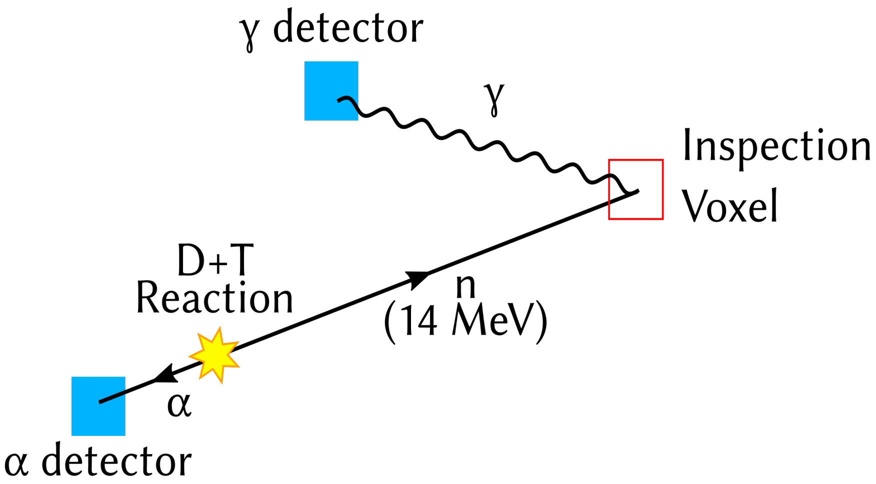
- Given the following nuclei, please report if they are good for INAA and/or PGNAA.

- B-10, Cd-113, Pb-207, C-12, O-16, N-14
- Au-198, W-186,V-51,Co-59

ASSOCIATED PARTICLE IMAGING NEUTRON TECHNIQUE

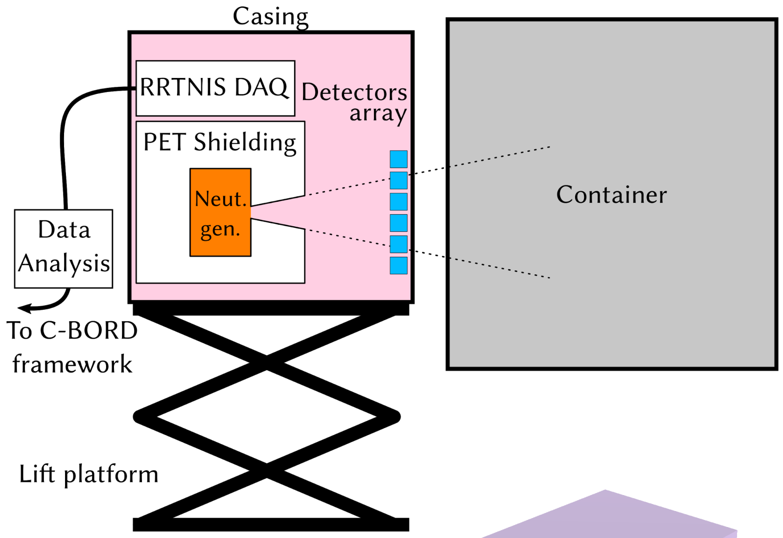
Tagged Neutron Inspection Technique

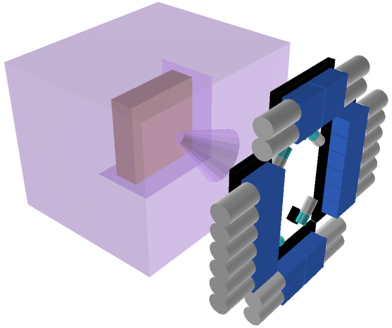
- Fast neutrons (14 MeV) from:
  D + T → α + n
- The collinear α tags the n.
- Voxel selection is given by time-of-flight (ToF) measurement and α direction.
- The γ spectrum at selected ToF depends on the voxel material.



TNIS Conceptual Design

- TNIS is fully contained in a movable casing.
- γ detectors are in a back-scattering configuration.
- The whole system is moved to be aimed at the inspection voxel.
- (for example C-BORD 20 large (5” x 5” x 10”) NaI + 4 $LaBr_3$ (3” x 3”) detectors)





Rapidiy relocatable tagged neutron inspection system

- RRTNIS is a second line inspection system
- Voxel position from X-ray scan
- Inspection time: 20 minutes
  - 10 minutes irradiation
  - Alignment and software analysis

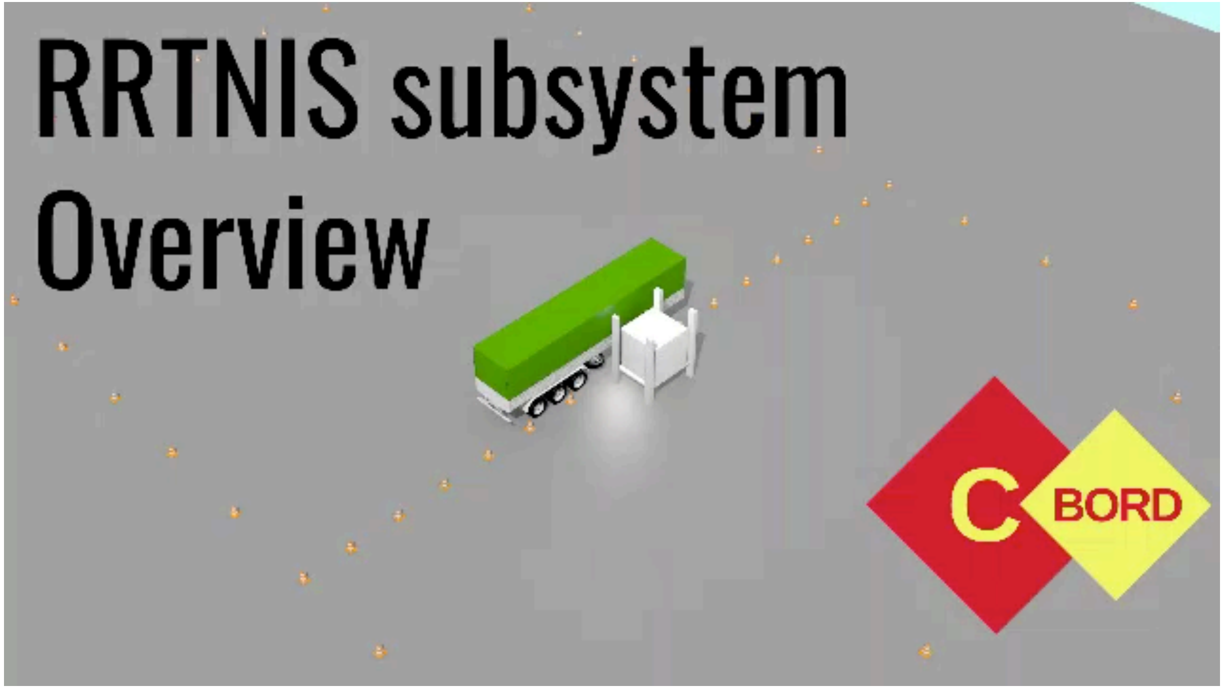
WHAT IS THE TECHNOLOGICAL METHOD BEHIND RRTNIS?

- The Tagged Neutron Inspection System combines the technology of inelastic neutron scattering with the associated particle time-of-flight spectroscopy to obtain an effective and accurate system for detection and identification of explosives and contraband drugs.

- In the TNIS, high energy neutrons are produced in a sealed tube neutron generator with an energy of 14 MeV and emitted isotropically from the source.

- Approximately 50 million neutrons are produced each second, and the units have demonstrated an average lifetime of about 2,000 hours of operation.

RRTNIS at demonstration site



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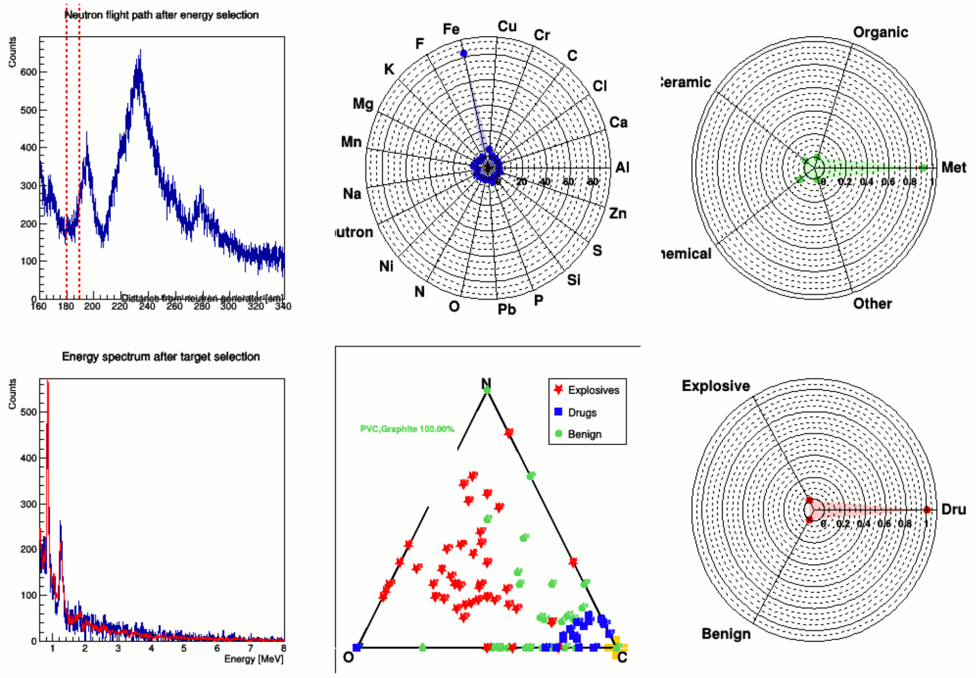
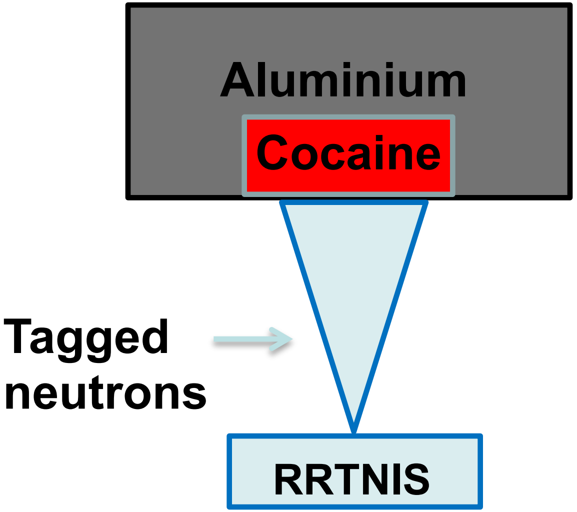
RESULTS

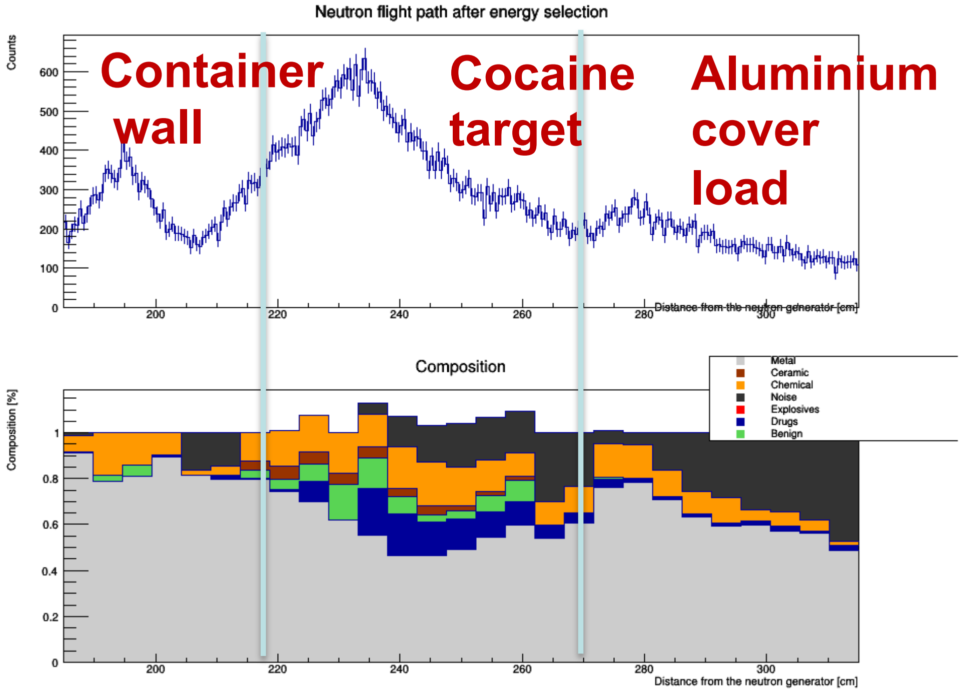
- **Peaks on the neutron flight path reflect changes in material/density**
- **The energy distribution changes as a function of depth**
- **Identification of the elements present**
- **Classification according to material type (metallic, organic, etc.)**
- **Differentiation between benign organic materials (wood, cotton, etc.) and explosives or drugs**



COCAINE TARGET HIDDEN IN AN ALUMINIUM COVER LOAD

Università degli Studi di Padova
INFN Istituto Nazionale di Fisica Nucleare





FAST NEUTRON AND GAMMA RAY TRANSMISSION

Interaction of neutron with the atoms

- The interaction of neutrons with the atoms described by the total microscopic cross-section σ_t, expresses the probability that a neutron of a given energy interacts with the atoms of the traversed material and it is defined as the sum of the microscopic cross section scattering σ_s and the microscopic cross-section absorption, σ_a

$$\sigma_t = \sigma_s + \sigma_a$$

Attenuation of neutrons

- The attenuation of neutrons during their passage through material medium depends not only on the microscopic cross-section but also on the number of nuclei within this environment.
- The physical quantity bound these two parameters, called total macroscopic cross-section denoted Σ_t and defined by

$$\Sigma_t = \frac{N_A \rho}{A} \sigma_t$$

Macroscopic cross-section

$$\Sigma_t = \frac{N_A \rho}{A} \sigma_t$$

N_A= Avogadro Number

A= Atomic Mass

ρ=density (g cm^{-3})

Σ_t has the dimensions of the inverse of the length, their unit is cm^{-1}

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Attenuation of neutrons

- In the same way as a beam of photons, when the parallel beam of monoenergetic neutrons through a material medium, it will be attenuated due to absorption and scattering.
- The attenuation of neutrons in matter follows the following law:

$$I = I_0 \; e^{-\Sigma_t x}$$

Where I_0 and I are respectively the intensities of neutrons unmitigated and mitigated

x (cm) is the thickness of the material medium

Σ_t represents the total macroscopic cross-section

Exercise

- How much will a 10 MeV neutron beam be attenuated, passing through a 1 cm thick lead absorber?

Knowing that:

Atomic weight Pb=207.21 and its density is 11.3 g cm^{-3}

Total cross section 5.1 b.

- $\Sigma_t = \frac{N_A \rho}{A} \sigma_t = \frac{11.3\ g}{cm^3} \frac{6.023\ 10^{23}\ atoms}{mole} \frac{mole}{207.2\ g} 5.1\ barn =$
- $\frac{I}{I_0} = e^{-\Sigma_t x} =$

Neutron interrogation for radiography and elemental analysis

- Fast Neutron and gamma ray transmission (FNGT)
- FNGT technique has a very good resolving power to determine the average atomic number of compounds with low atomic number (Z< 13).

FNGT

- Measure the attenuation for neutron and gamma.

$$I_n/I_n^0 = \exp(-\mu_n \rho x) \qquad I_g/I_g^0 = \exp(-\mu_g \rho x)$$

- The ratio R, material dependent, is calculated:

$$R = \frac{\mu_n}{\mu_g} = \frac{\ln(I_n/I_n^0)}{\ln(I_g/I_g^0)}$$

- Average atomic number from the ratio of gamma to fast-neutron attenuation

R-values

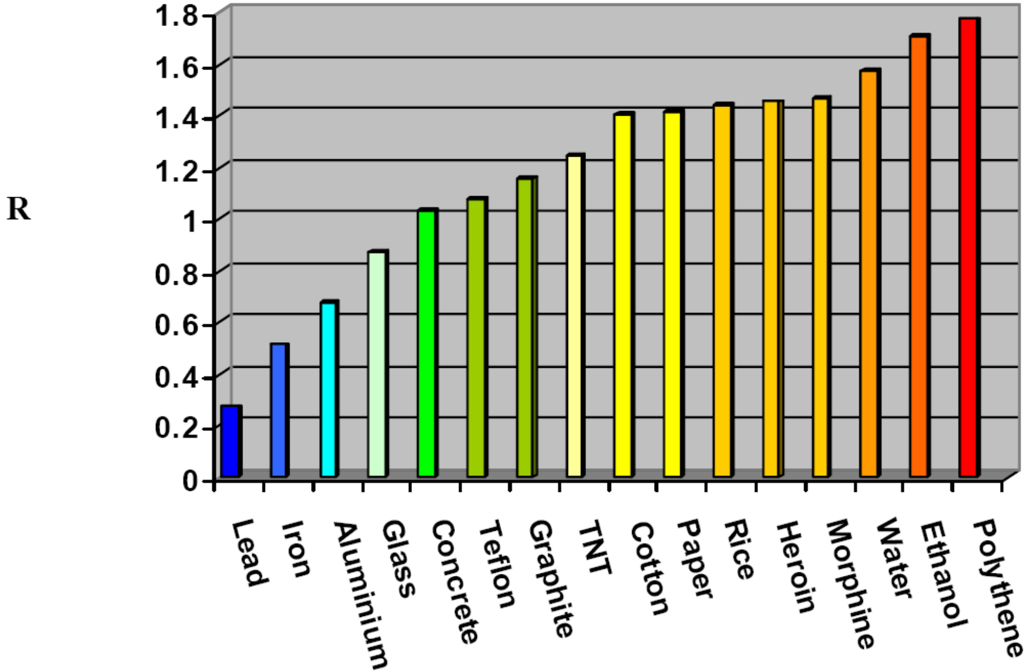


Figure 1. Calculated R values for a range of materials, using 14 MeV neutrons and ^{60}Co gamma rays.

FNGT

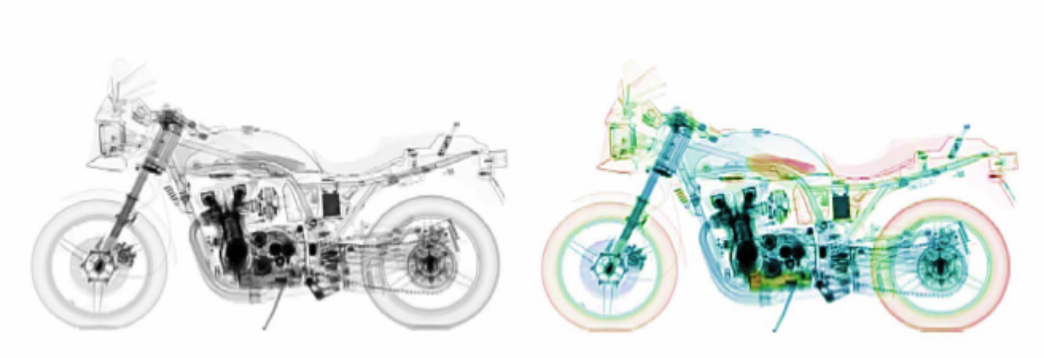
FNGT is very promising technique for solving many industrial problem.

- On of such complicate problem is detection of hydrocarbon deposit and corrosion in industrial pipe
- Efficient and highly automated metallurgical processes require the on-line control of coke moisture which assures high steel quality and fuel economy.

The technique

- Average atomic number from the ratio of gamma to fast-neutron attenuation

CSIRO

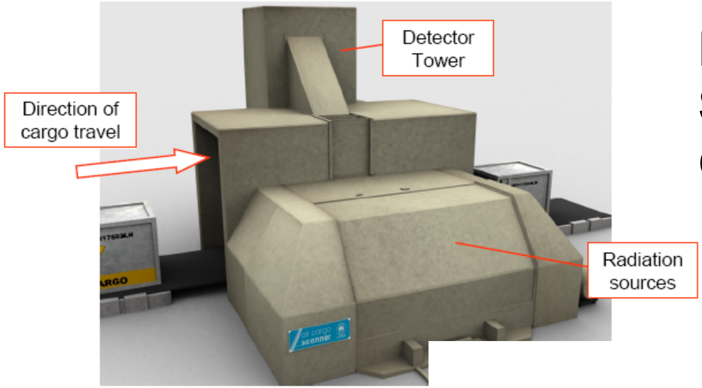


CSIRO

Air Cargo Screening using a Fast Neutron and Gamma-Ray Radiography Scanner

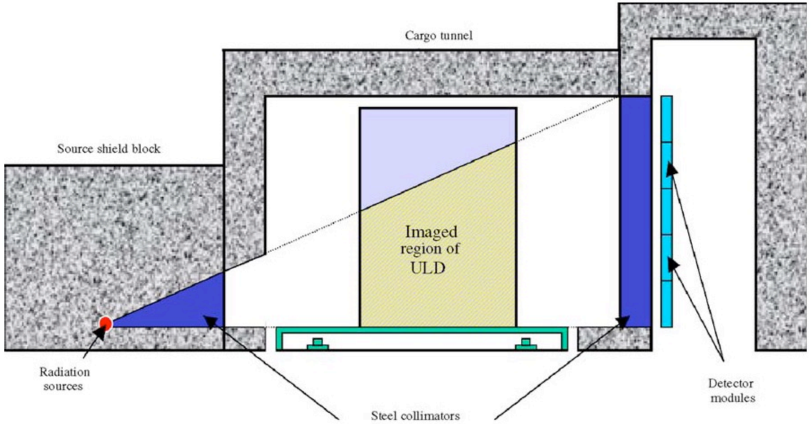
CSIRO

CSIRO Air Cargo Scanner at Brisbane International Airport



Neutron source:
Sealed tube D+T neutron Generator (14 MeV) 10^{10} n/s

Gamma source
^{60}Co source (1.17,1.33 MeV) 185 GBq



HOW DOES IT WORK?

Measure attenuation for neutrons:

$$I_n/I_n^0 = \exp(-\mu_n \rho x)$$

and for gammas:

$$I_g/I_g^0 = \exp(-\mu_g \rho x)$$

Finally the ratio R is determined

$$R = \frac{\mu_n}{\mu_g} = \frac{\ln(I_n/I_n^0)}{\ln(I_g/I_g^0)}$$

R is material dependent

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Fast neutron radiography scanner for the detection of contraband in air cargo containers

J.E. Eberhardt, S. Rainey, R.J. Stevens, B.D. Sowerby*, J.R. Tickner
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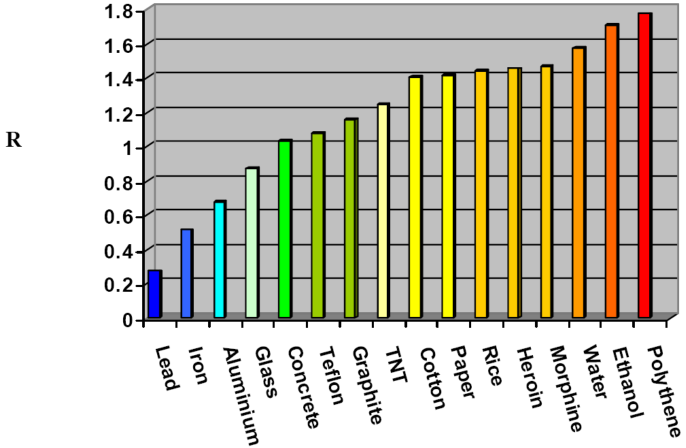


Figure 1. Calculated R values for a range of materials, using 14 MeV neutrons and ^{60}Co gamma rays.

CSIRO

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME **5**, 104701 (2002)

Processing of interlaced images in 4–10 MeV dual energy customs system for material recognition

S. Ogorodnikov and V. Petrunin
Efremov Scientific Research Institute, St.-Petersburg, Russia

$$R(E_1, E_2, t, Z) = \frac{\ln T(E_1, t, Z)}{\ln T(E_2, t, Z)} = \frac{\overline{\mu}_{\rm eff}(E_1, t, Z)}{\overline{\mu}_{\rm eff}(E_2, t, Z)}.$$

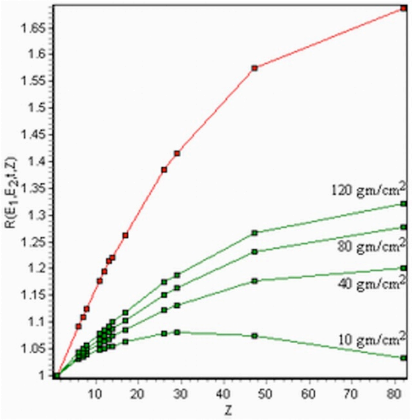


FIG. 3. (Color) Ratio $R(E_1, E_2, t, Z)$ vs atomic number Z for barriers with different mass thickness (green curves). Values correspond to the following materials: H, C, N, O, Na, Mg, Al, Si, Cl, Fe, Cu, Ag, and Pb. A red curve illustrates monochromatic 8/4 MeV gamma beams. Ratio is normed to hydrogen. Analytical calculation for pencil beams geometry.

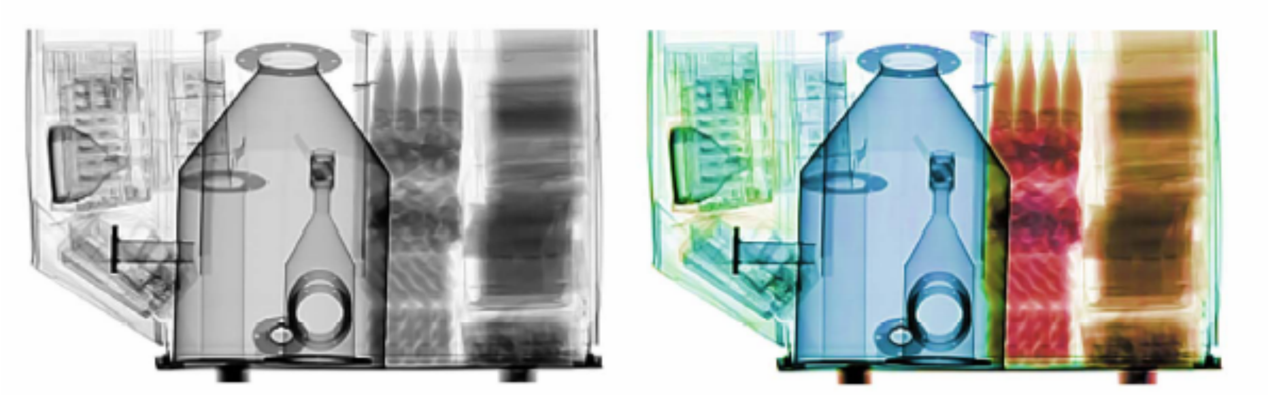
CSIRO:

R_{Carbon}/R_{Lead}≈4.4

Predicted dual energy system with 4/8 MeV monochromatic beams

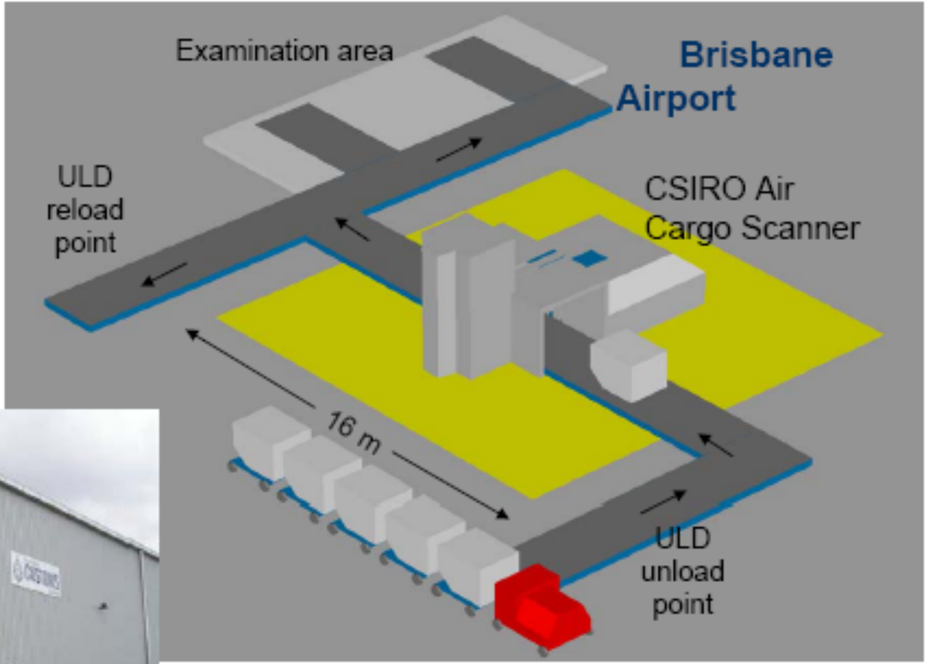
R_{Lead}/R_{Carbon}≈1.6

Reference Scanner: ULD Loaded with Mixed Cargo



From left-to-right, the cargo contains assorted computer equipment, heavy steel industrial items, mixed boxes of food stuffs (including bottled drinks, frozen meat and fish, boxed apples) and boxes containing office files and papers.

Customs Scanner Facility at Brisbane International Airport



Important points

1) **R has to be measured for all pixels**
   - ➢ **need of high counting statistics.**

2) **In case of inhomogeneous cargo, the scanner measures quantities averaged along the radiation path.**
   - ➢ **Determination of R for single material layer is performed, in some cases, by software.**

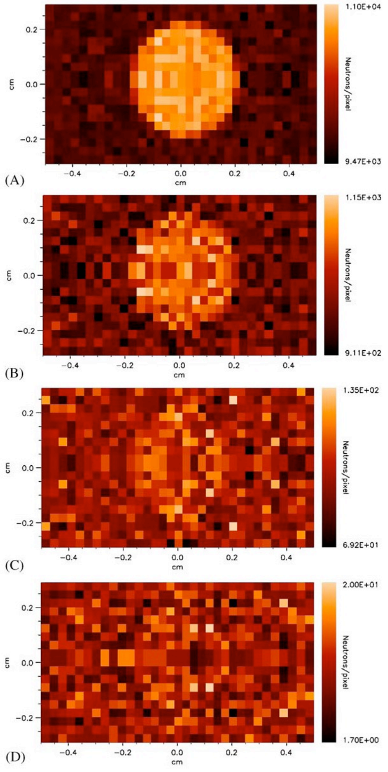


Fig. 5. Monte-Carlo simulations of point-source fast-neutron radiography of a 4 mm deep hole in a 5 cm thick iron plate. The number of impinging neutrons per pixel was varied between 31538 (A); 3154 (B), 315 (C) and 31.5 (D) corresponding with a FOM of 110, 35, 11 and 3.5, respectively.

DETECTION SYSTEM FOR FNGT

Organic Scintillator

- Organic scintillators produce light by both prompt and delayed fluorescence. The prompt decay time is typically a couple of nanoseconds, while the delayed decay time is normally on the order of hundreds of nanoseconds.

Organic Scintillator

- The majority of the light is produced by the prompt decay; however, the amount of light in the delayed component often varies as a function of the type of particle causing the excitation (Knoll 2000).
- The variation in the amount of light produced by delayed fluorescence can be utilized to distinguish different types of particles; this technique is known as pulse shape discrimination (PSD).

Neutron and gamma discrimination

- Neutron interactions in organic scintillators produce scattered protons through elastic scattering; protons have a short range and generate a high concentration of triplet states, which decay by delayed fluorescence.

Neutron and gamma discrimination

- By contrast, gamma ray interactions in organic scintillators produce scattered electrons. Electrons have a longer range than protons and generate a lower concentration of triplet states (electrons are more likely to produce excited singlet states, which decay by prompt fluorescence) (Zaitseva 2011a).

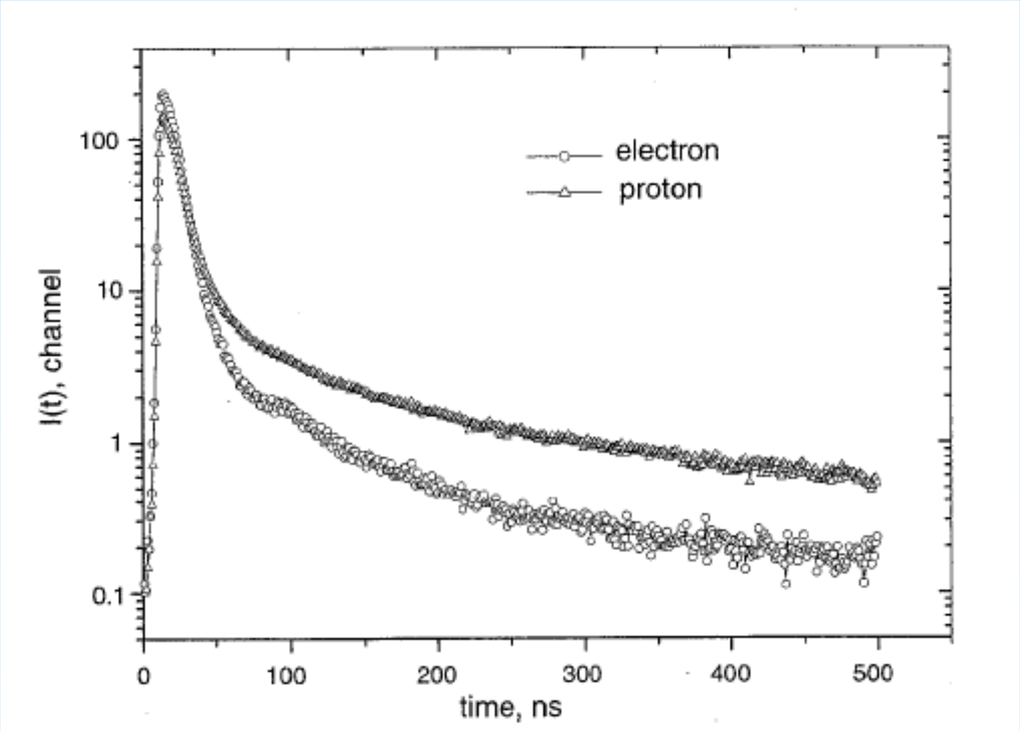
Neutron and gamma discrimination

- The difference in the pulse shape of the signal as a result of the ratio of prompt to delayed fluorescence produced by different types of radiation makes PSD a popular method of high-energy neutron detection in an environment where gamma

PSD

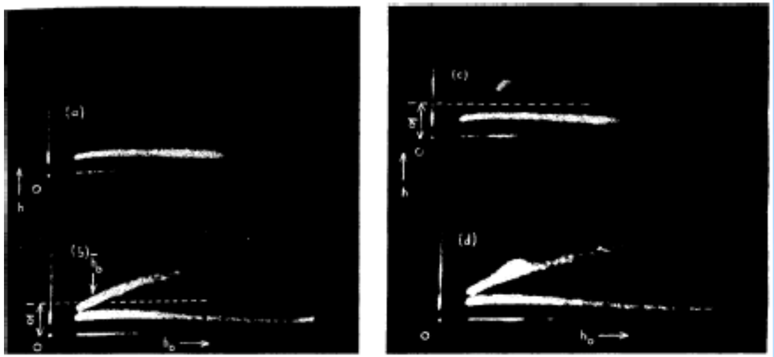
- The PSD techniques used to distinguish between the pulses from neutrons and the pulses from gamma rays rely on the differences in the pulse shapes produced. The pulses generated by neutrons will have a longer tail than the pulses generated by gamma rays, as the neutron pulses are the result of triplet state interactions (delayed fluorescence) and the pulses produced by gamma rays are the result of singlet state de-excitation (prompt fluorescence). Thus, the difference in the ratio of the charge in the tail of the pulse to the total charge in the pulse

Liquid Scintillator with Pulse shape discrimination



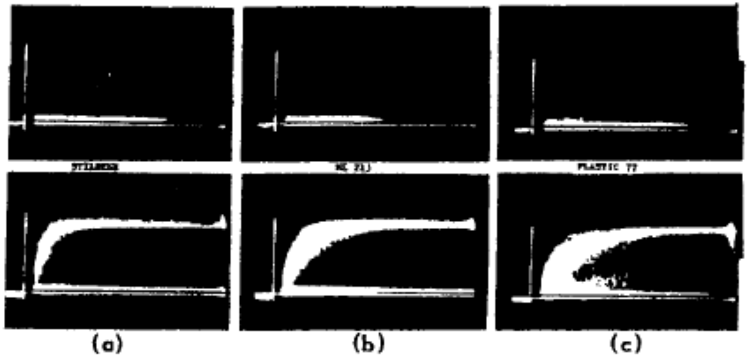
N.V. Kornilov et al.,
NIM A497 (2003) 467- 78

Discovery of PSD



F.D. Brooks et al., IRE NS (1960) 35 - 38

Stilbene NE213 plastic 77



F.D. Brooks, NIM 4 (1959) 151 - 163

PSD with stilbene

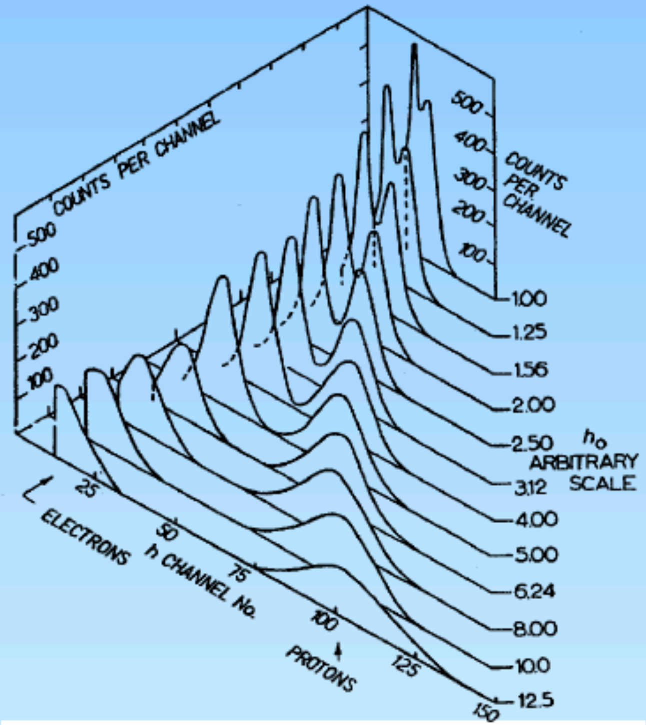
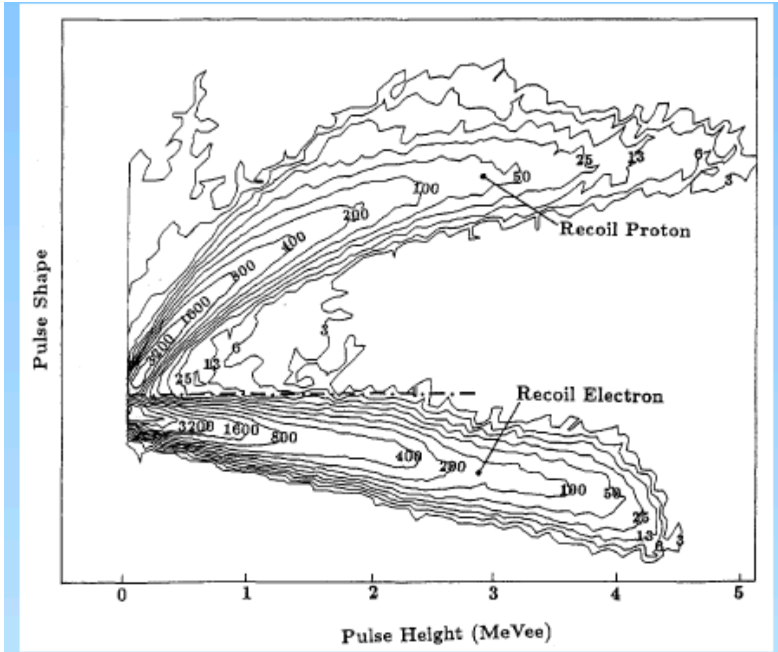
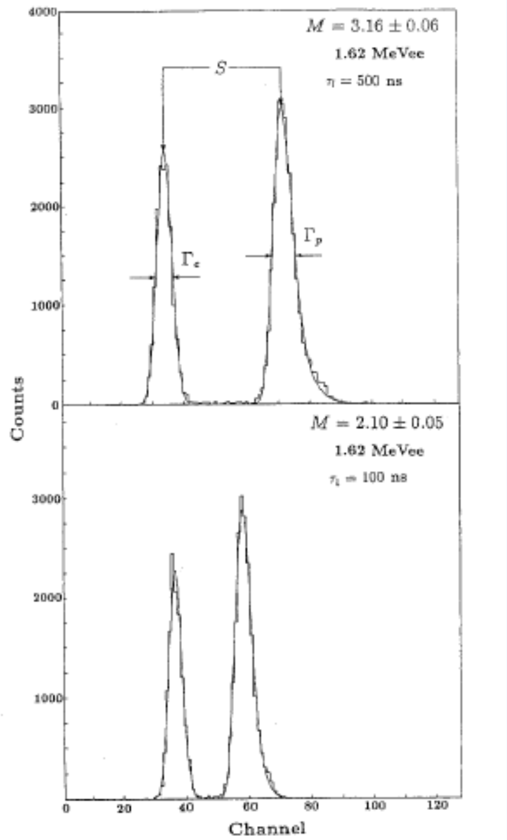


Figure of Merit



PS-analysis for Am/Be-source
Figure of Merit : M = S / ($\Gamma_e + \Gamma_p$)
J.R.M Annand, NIM A262 (1987) 371



EXERCISE

A standard figure of Merit

- A fast neutron detector that is appropriate for use in situations where gamma rays are present is one that can produce clearly separated neutron and gamma ray signals.
- The separation between the neutron and gamma ray signals can be quantified and used to determine a performance metric.

.

A standard figure of Merit

- A standard figure of merit (FOM) has been identified for fast neutron detectors and is used to establish their ability to discriminate between pulses generated by gamma rays and pulses generated by neutrons. The FOM is calculated after PSD has been performed to identify the neutron and gamma ray pulses.

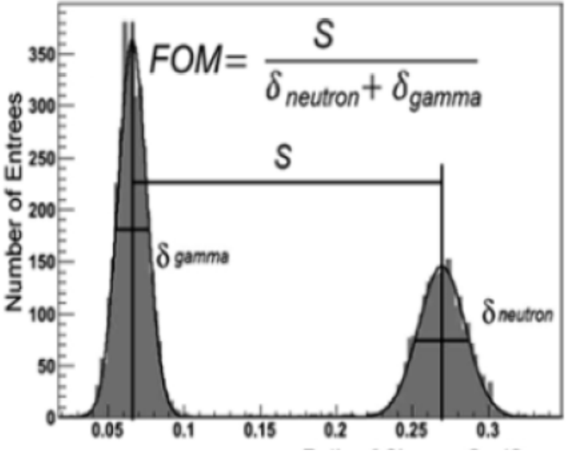
FOM

- The FOM is calculated from the histogram of the PSD versus peak height data. The FOM is defined as (note that this definition assumes that the pulse distributions are Gaussian):

$$FOM = \frac{S}{\delta_{neutron} + \delta_{gamma}}$$

S ≡ the distance between the gamma ray and neutron peaks
δ ≡ the full width at half maximum (FWHM) of the peaks.

FOM

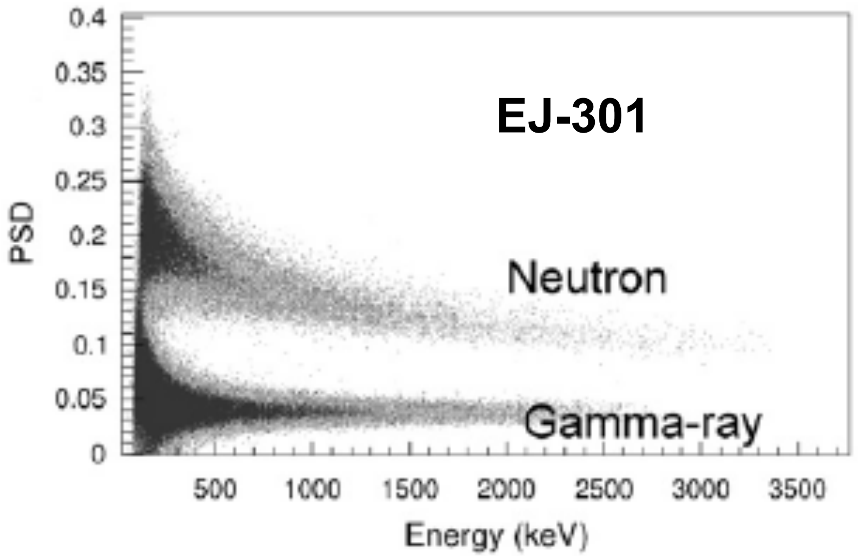

FOM= S / (δ neutron + δ gamma)
S
δ gamma
δ neutron
Number of Entrees
350
300
250
200
150
100
50
0
0.05
0.1
0.15
0.2
0.25
0.3

FOM

- The definition of the FOM illustrates that the larger the FOM the better the performance of the detector for gamma ray discrimination.
- A baseline performance requirement can be established by starting with the definition that for two peaks to be considered well separated S > 3(**σ**gamma + **σ**neutron), where **σ** is the standard deviation.

$$FOM \geq \frac{3(\sigma_{neutron}+\sigma_{gamma})}{2.36(\sigma_{neutron}+\sigma_{gamma})} = 1.27$$

Liquid and Plastic Scintillator PSD



EJ-301 liquid scintillator (NE213 type) toxic, low flash point (26 C)

EJ-309 liquid scintillator non toxic, higher flash point (144 C)

EJ-299-33 Plastic with PSD

ELJEN TECHNOLOGY


C BORD
Effective Container Inspe
BORDer Control Points
This equipment is part of a project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°653323.

THANK YOU

HOW GOOD IS A "GOOD" DETECTOR ?

Basic statistical and probabilistic elements of assessing performances of a detection system

a) Suppose to have a detector with binary output ("yes" or "no") and to have a binary measure of "truth" reflecting the actual *presence* or *no presence* of a threat in the volume inspected by the detector.

b) Also suppose to run a number of tests, recording for each test the true status of the investigated volume and the detector response.

c) Record the results in a 2 x 2 table where a, b, c, d reflect the number of times that a particular combination of detector reading and true presence or absence of a threat occurs (out af a total of N = a+b+c+d total tests)

The table reads as follows :

a+c tests run with threat present
b+d tests run with threat absent

detector response → random variable

detector status → D

true presence of threat → T

		Truth	
		Yes	No
Detector reading	Yes	*a*	*b*
	No	*c*	*d*

Sensitivity and Specificity

- *Sensitivity* **reflects the ability of the detector to identify a threat if the threat is present (i.e. the detector gives an "alarm" when it should).**

- *Specificity* **reflects the ability of the detector to identify a threat only if the threat is present (i.e. the detector does not give an "alarm" when it should not).**

Conditional probabilities:

Let's define the following conditional probabilities:

P(D = yes / T = yes) = a/(a + c) True Positive Fraction TPF → *(sensitivity)*

P(D = yes / T = no) = b/(b + d) False Positive Fraction FPF

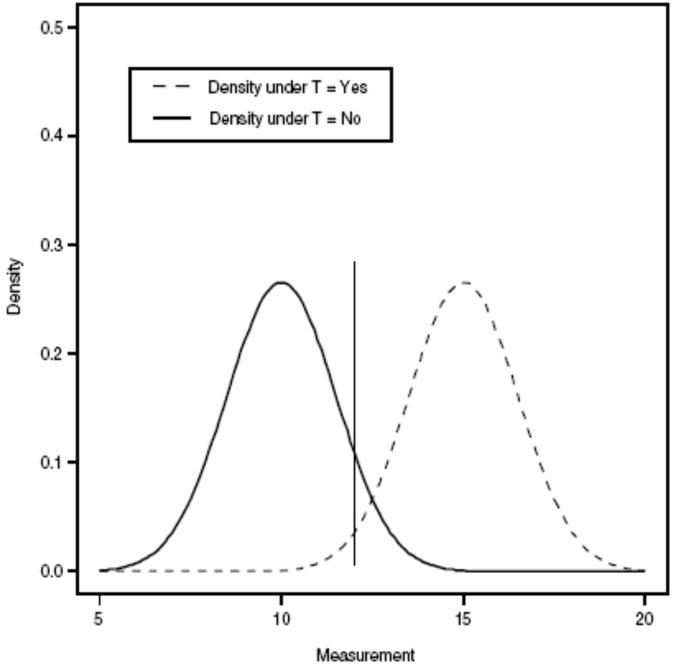
P(D = no / T = no) = d/(b + d) True Negative Fraction TNF → *(specificity)*

P(D = no / T = yes) = c/(a + c) False Negative Fraction FNF

***Note that:* *specificity* is defined as (1 – False Positive Fraction)**

		Truth	
		Yes	No
Detector reading	Yes	*a*	*b*
	No	*c*	*d*

- **Typically a detection system is based on measurements of some parameter that has a range of values expected in absence of a threat and a different range of values expected in presence of a threat (e.g. in the case of neutron inelastic scattering the parameter could be the χ^2 value obtained comparing the measured γ-ray spectrum with that of explosives and with that of benign materials).**
- **The ranges of measured values of such parameter in presence or absence of a threat can be expressed as probability densities.**



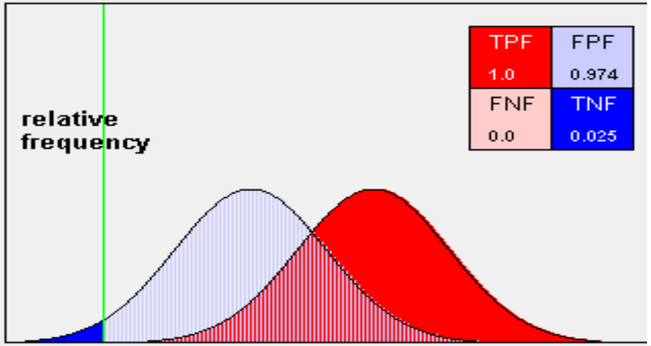
Dashed line (high values of the parameter)

Response of detector = YES

Solid line (low value of the parameter)

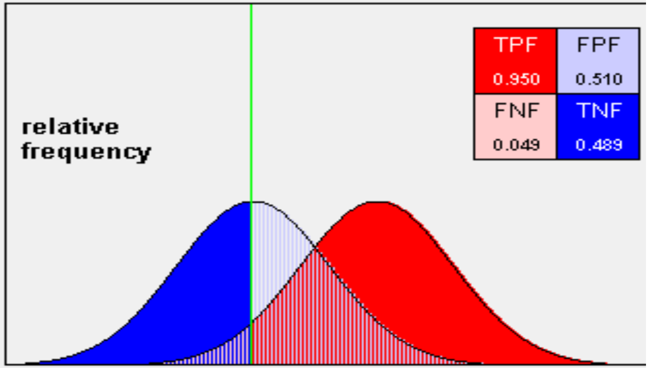
Response of detector = NO

Cutoff threshold will define the "working conditions" of the detection system



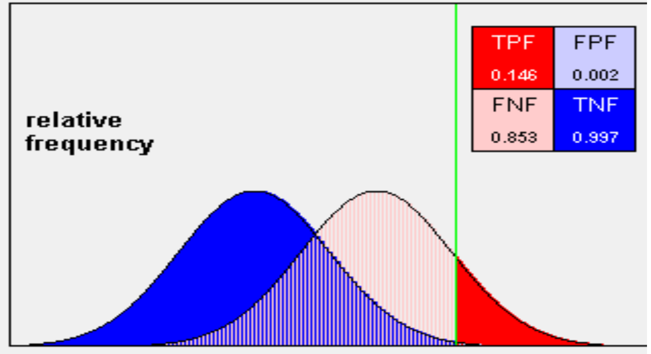
<u>Low Cutoff Threshold:</u>

High TPF (*sensitivity*) → all the tests where there is a real threat are correctly recorded by the detector, however Very High FPF → Very Low TNF (*specificity*) → the detector gives a large number of "alarms" when there is no real threat



<u>Medium Cutoff Threshold:</u>

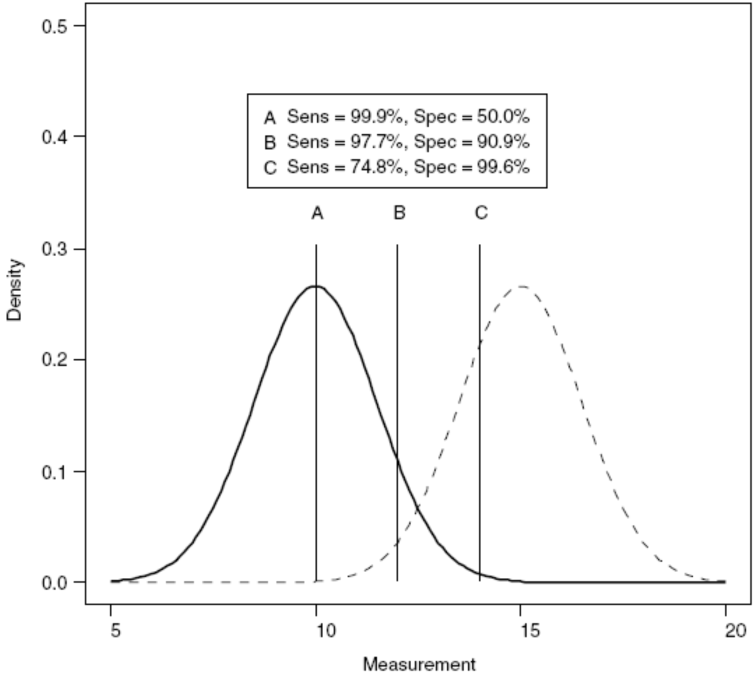
Good TPF (*sensitivity*) → most of the test where there is a real threat are correctly recorded by the detector, but Too High FPF → Too Low TNF (*specificity*) → the detector still gives a large fraction of "alarms" (about 50% of the total) when there is no real threat



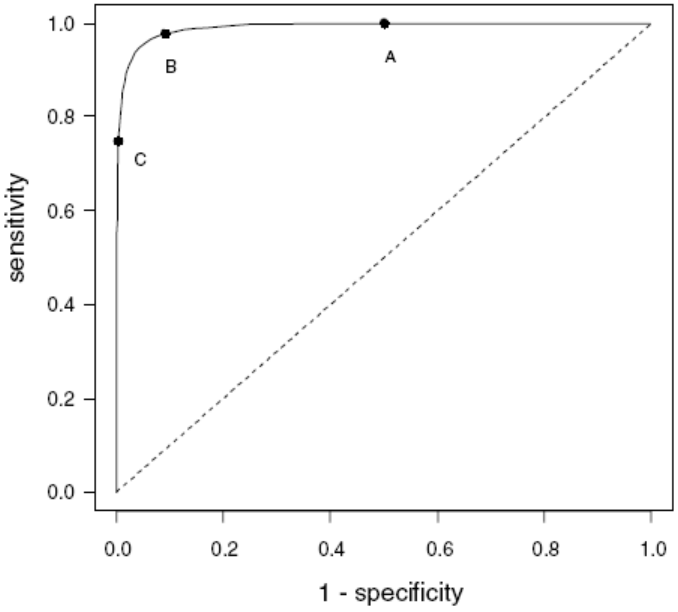
<u>High Cutoff Threshold:</u>

High TNF (*specificity*) → Low FPF → the detector does not give an "alarm" unless there is a real threat, but Very Low TPF (*sensitivity*) → the detector is not able to give an "alarm" in many cases when there is a real threat

Examples of variation of *sensitivity* (TPF) and *specificity* (1 – FPF) as a function of the cutoff threshold



The "Receiver Operating Characteristic" curve (ROC)



Used originally to evaluate the performances of a radio receiver as a function of signal/noise ratio, the ROC curve is used as a 2-D representation of the performances of a test (in our case of a detection system) representing the correlation between FPF (1-*specificity*) vs TPF (*sensitivity*) as a function of the cutoff threshold set on the detector itself.

The points A, B, C show the response of the detector system changing the cutoff threshold as shown in the previous slide

The dashed diagonal is the line where TPF = FPF meaning that the test has no diagnostic value (the detector responds like flipping a coin…)

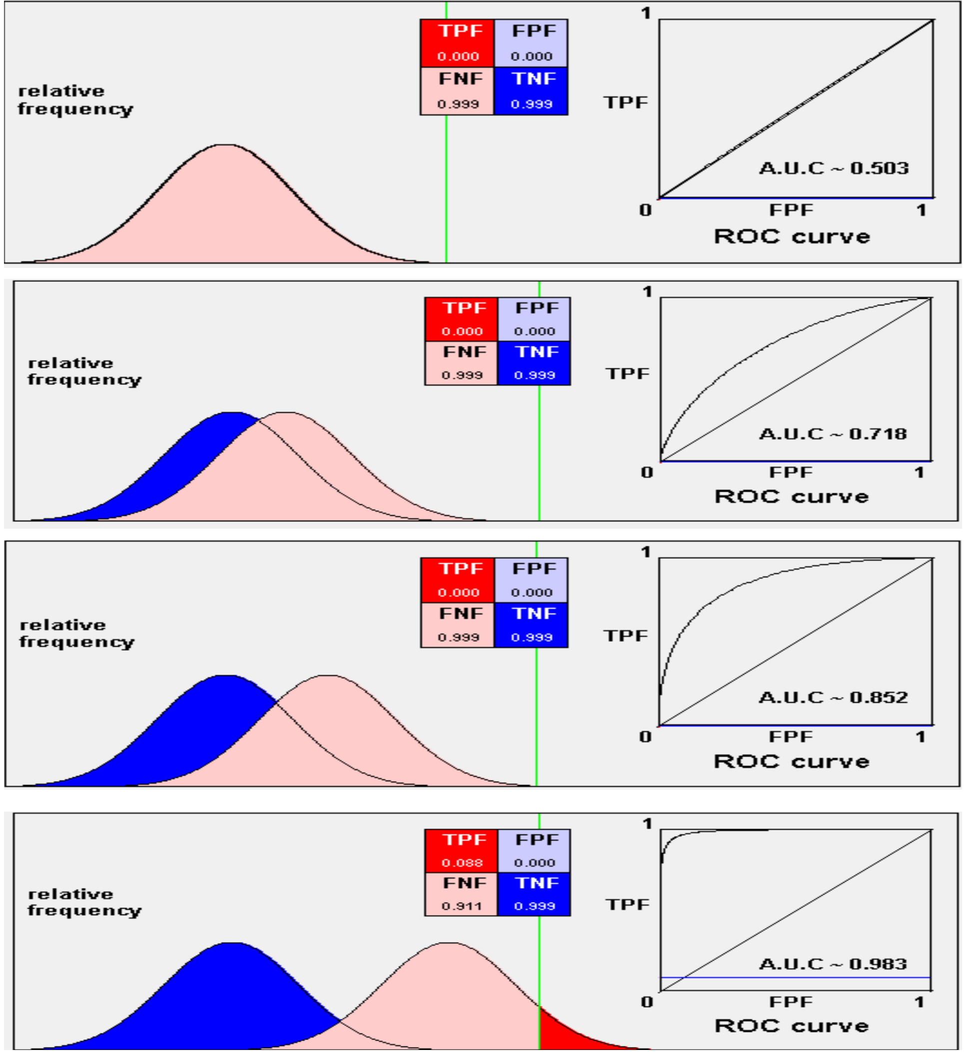
More observations about the ROC curve:

Notice two particular points on the ROC :

a) The point (1,1) → minimum cutoff threshold → 100% *sensitivity* and 0% *specificity* → every test performed by the detector yields an "alarm"

b) The point (0,0) → maximum cutoff threshold → 0% *sensitivity* and 100% *specificity* → none of the test performed by the detector yields an "alarm"

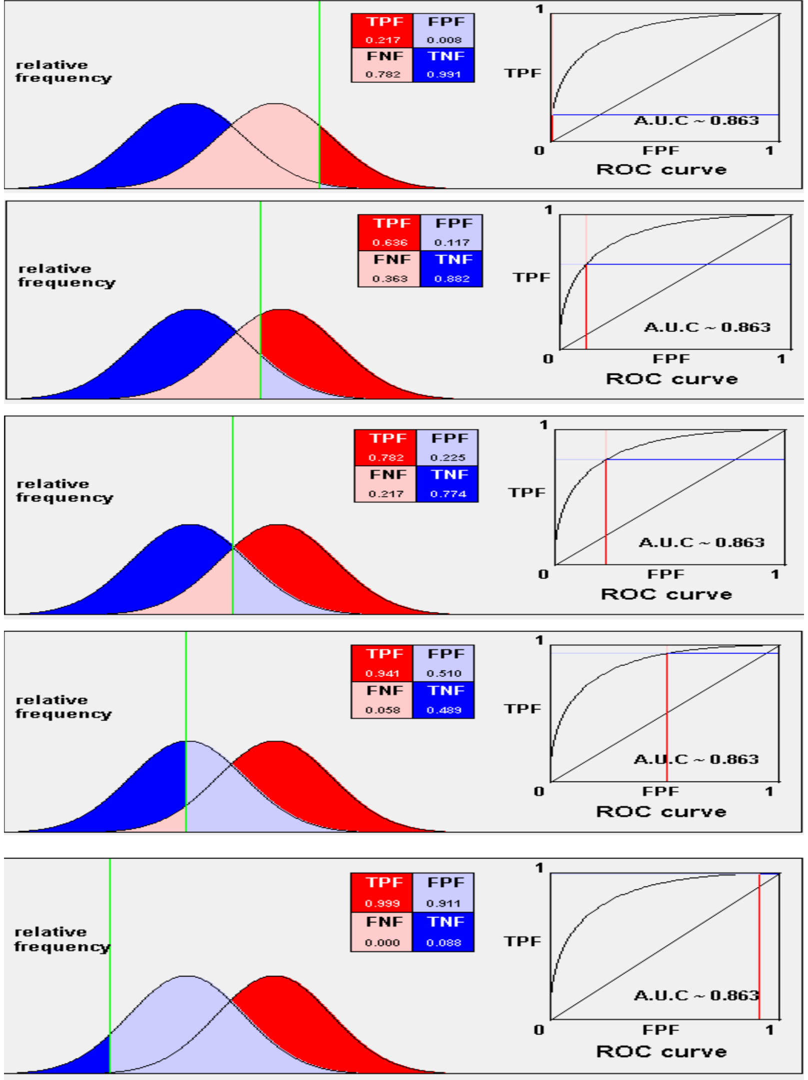
The ideal test corresponds to an ROC curve beginning at point (0,0) and jumping immediately to nearly 100% sensitivity and 100% specificity → this corresponds to a complete de-coupling of the two probability densities of the measurement as can be seen in the next slide



From top to bottom panel one sees the effect of the separation between the probability density curves of a detection system on the relative ROC curve.

For total overlap the ROC curve corresponds to the diagonal (no diagnostic value of test), as the two curves de-couple more and more the ROC curve is further away from the diagonal.

The Area Under the Curve (A.U.C.) defines the general "quality" of a detector → the larger A.U.C. the better the expected detector performances *regardless the cutoff threshold set*



For a given overlap between the two probability densities (fixed A.U.C. → defines the overall detector "quality")

The cutoff threshold position defines the position on the ROC where one is using the detection system

Estimate of field performances of a detection system

Performance probability of interest:

- P(T = yes / D = yes)

"probability of true presence of a threat when an alarm occurs"

P(T = no / D = yes) = 1 - P(T = yes / D = yes)

"probability that no threat is present when an alarm occurs"

Estimate of field performances of a

- These two probabilities reverse the conditioning order → they do not correspond to TPF and FPF respectively. The difference being the following :

- TPF reads → "the probability of having an alarm out of all the tests where there is a real threat"

- P(T = yes / D = yes) reads → "the probability that an alarm is true out of all the detector alarms"

Estimate of field performances of a detection system

- FPF reads → "the probability of having an alarm out of all the tests where there is not a real threat"

- P(T = no / D = yes) reads → "the probability that an alarm is false out of all the detector alarms"

The probability P(T = yes / D = yes) that an observed alarm is true depends on the sensitivity and specificity of the test and moreover on the frequency of background and real threats via the Bayes' Theorem :

$$P(T=yes / D=yes) = \{P(D=yes / T=yes)P(T=yes)\}/P(D=yes)$$

Where P(D=yes) is the probability that a detector sets an alarm during use with or without a real threat during the tests. It is possible to express this probability in terms of known values through the Law of Total Probability by:

$$P(D=yes) = P(D=yes / T=yes)P(T=yes) + P(D=yes / T=yes)P(T=no)$$

that is:

$$P(D=yes) = (\textit{sensitivity})P(T=yes) + \{1- \textit{specificity}\}\{1- P(T=yes)\}$$

The important point is that the probability P(D=yes) depends on the technical characteristics of the detector and on the "position" along the ROC curve during the tests (*sensitivity* and *specificity*) but in particular on:

P(T=yes)

- Which is the unconditional probability of having a true threat among the total number of tests and therefore represents the:

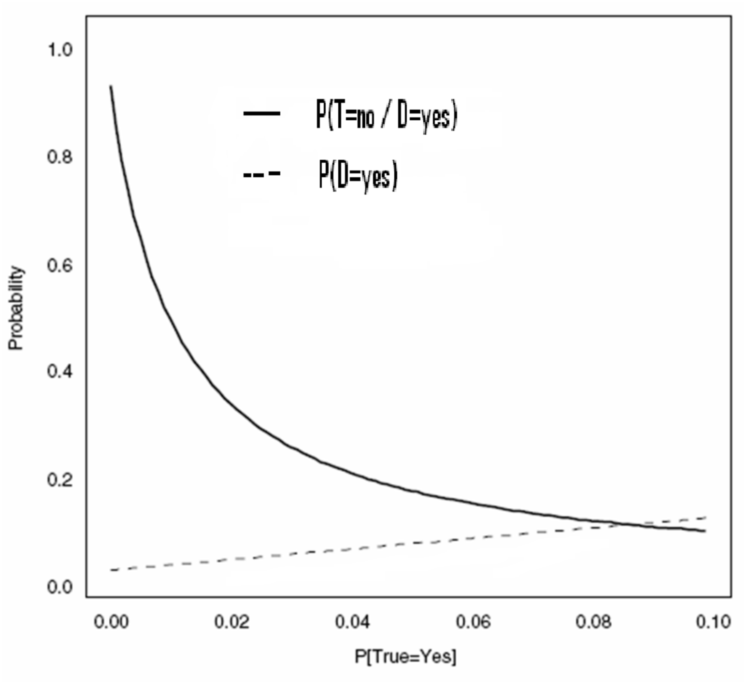
  - <u>frequency of true threats</u>

- Such frequency depends of course on the particular scenario, but for the application of new detection techniques to security is (fortunately !) an extremely small number

Such frequency depends of course on the particular scenario, but for the application of new detection techniques to security is (fortunately !) an extremely small number

This is an issue of paramount importance for the determination of the “field effectiveness” of a system →

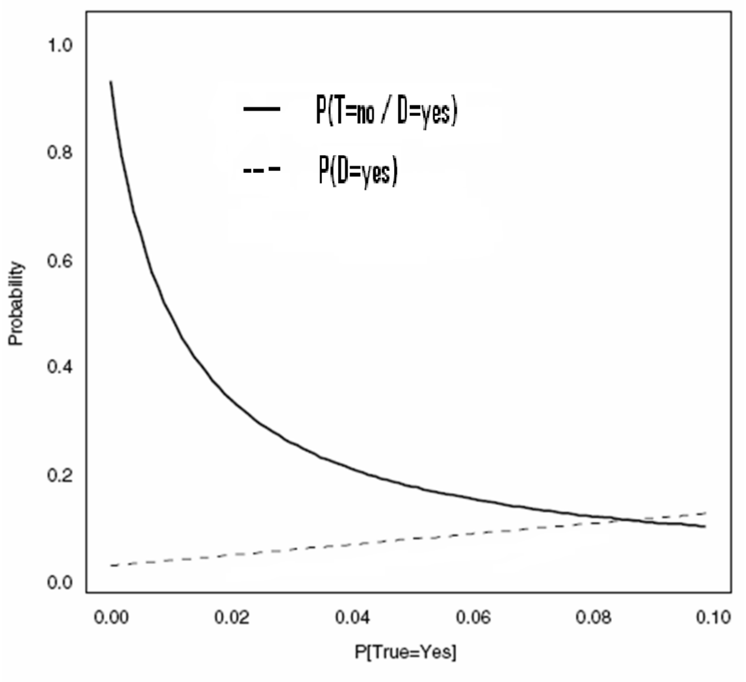
- in case of extremely low frequency of true threat (bomb in check-in luggage or plutonium in a sea container) even a system with very high sensitivity and specificity can have an unacceptably high probability that any observed alarm is false



Probability that the detector sets an alarm → P(D=yes) decreases linearly as the frequency of the real threat → P(T=yes) decreases

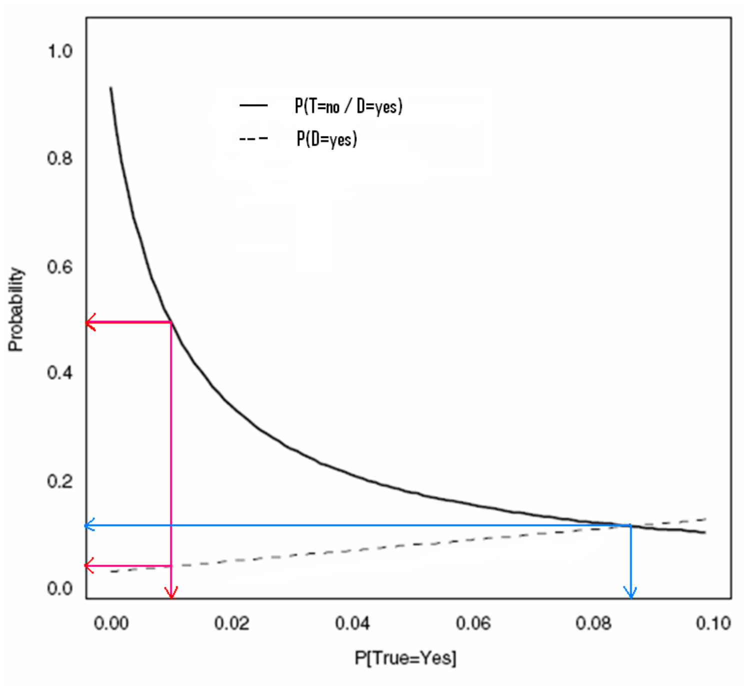
(dashed line)

Probability that no threat is present when an alarm occurs → P(T = no / D = yes) increases nonlinearly as the frequency of the real threat → P(T=yes) decreases (solid line)



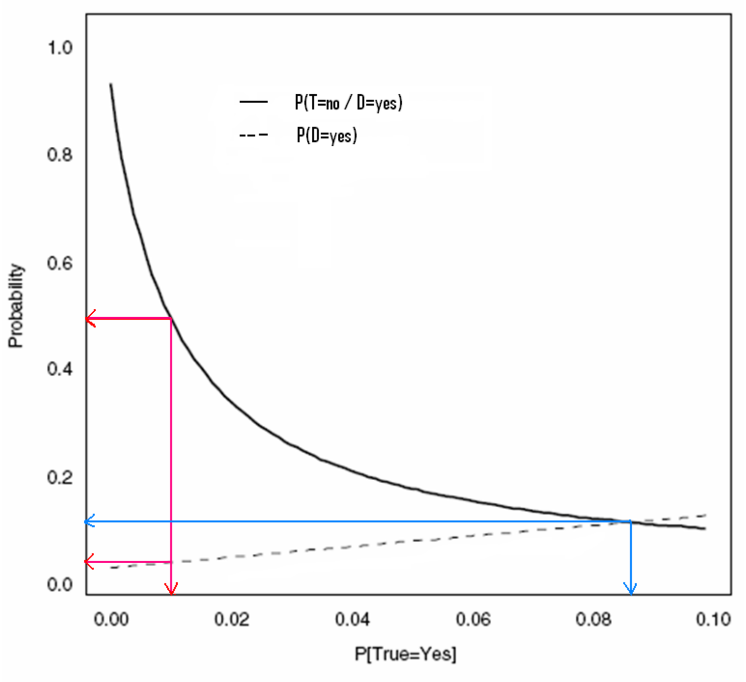
- *Sensitivity* = 99%
- *Specificity* = 99%

- The proportion of alarms that are false is close to 100% when the presence of a real threat is close to 0% → all the alarms will be false if there is no presence of real threat during the inspection tests



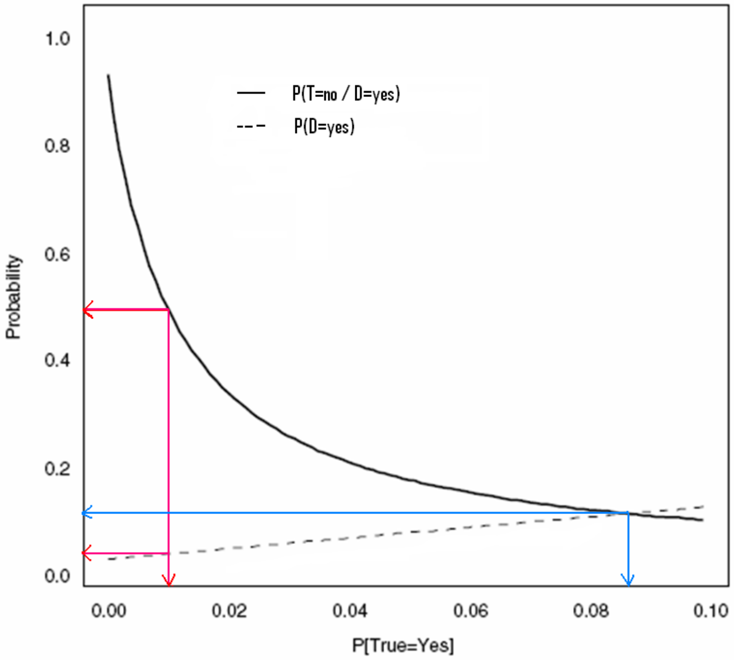
Blue line → about 8-9 real threat out of 100 tests (abnormally high probability of a real threat) → e.g. about 20 bombs for each commercial passenger flight !!!!

About 10 alarms of which 10% (about 1 alarm) are false



Red line → about 1 real threat out of 100 tests (still unreasonably high probability of a real threat) → e.g. about 2 bombs for each commercial passenger flight.

About 2 alarms of which 50% (about 1 alarm) are false



If one considers very large numbers (1 bomb every 1,000,000 suitcases) the probability to have an alarm during check-in luggage screening would be about 0.001 (1 every 5 aircrafts) but,

IT WILL BE FALSE !

with a probability of 99.9 %

Multi-stage and multi-detector systems

Combination of two detectors

1. Non-orthogonal system

→ the two detectors give responses based on measurements of similar parameters

→ They are used in “OR” mode → if either one gives an alarm the system responds positively

Multi-stage and multi-detector systems

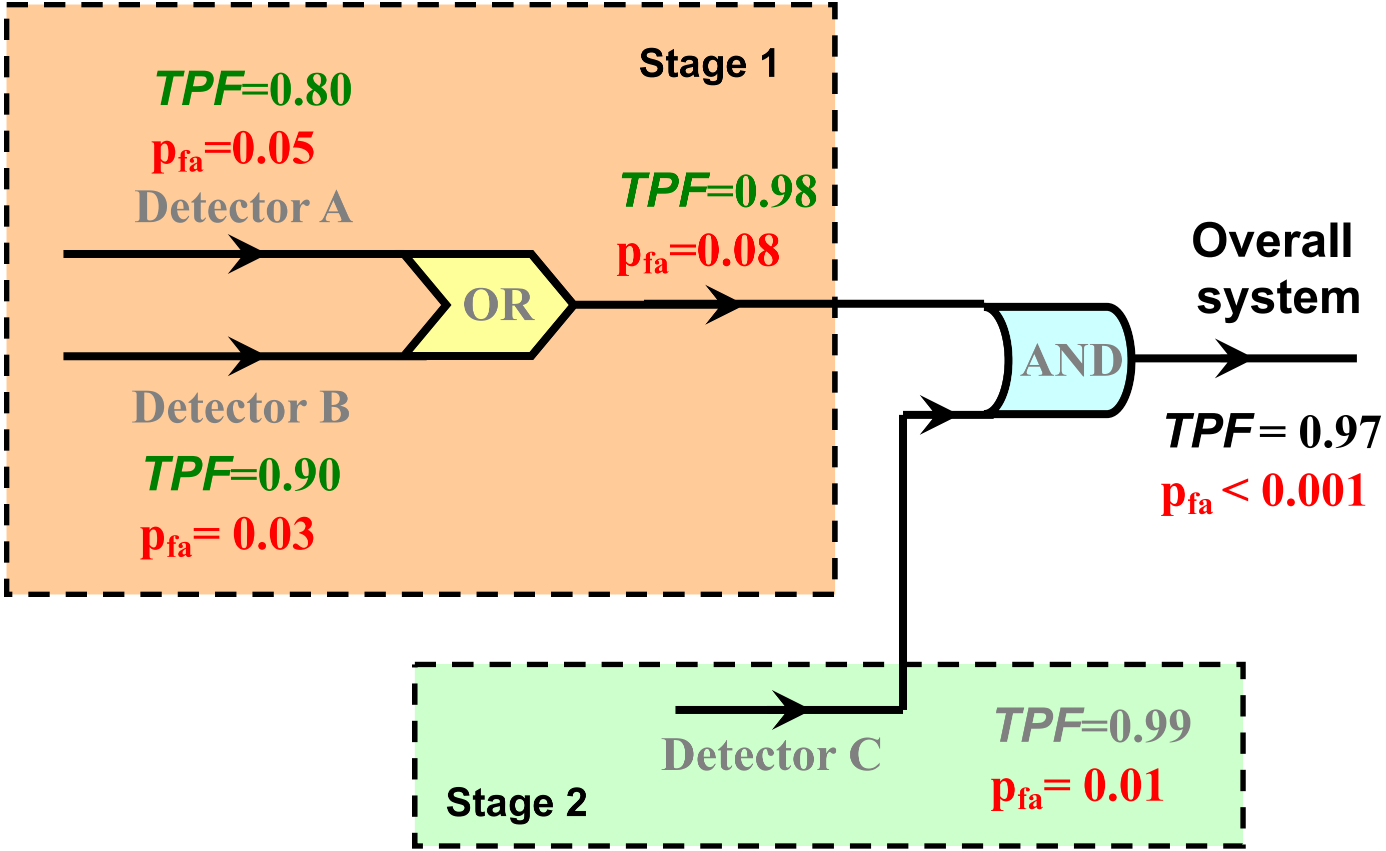
Combination of two detectors

- *2. Orthogonal system*

→ the two detectors give responses based on measurements of totally independent parameters

→ They are normally used in “AND” mode→ only if both detectors give an alarm the system responds positively

Combined detection probabilities for a multi-stage, multi-detector system



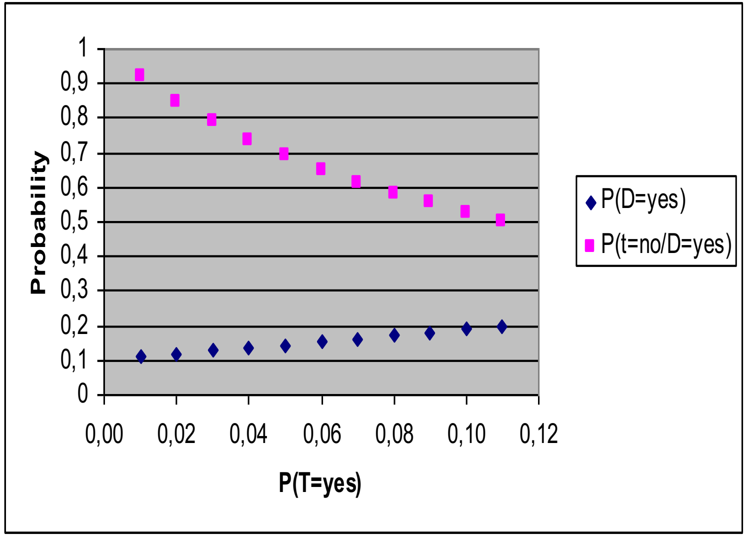
Performances of a single detector with *Sensitivity* = 90% and *Specificity* = 90%

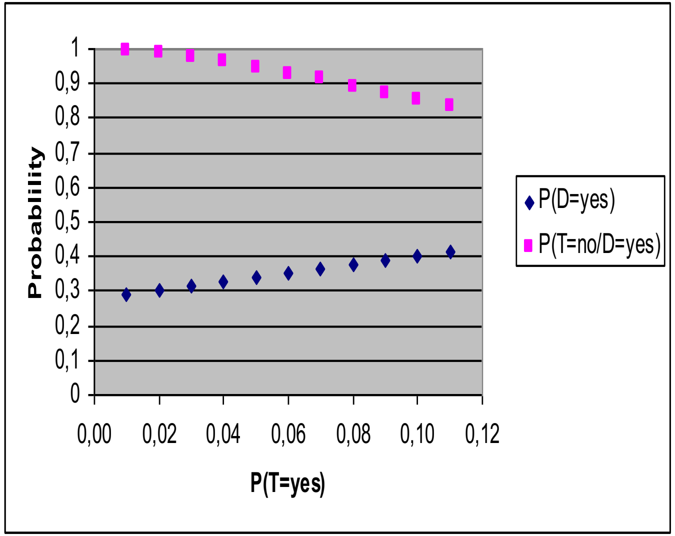
Performances of the "OR" combination of two detectors with:

Sensitivity 90% and 80%

Specificity 90%and 80%

The TPF (*sensitivity*) is largely increased but the field performances of the system for "rare events" are ***worse*** than those of a single detector !

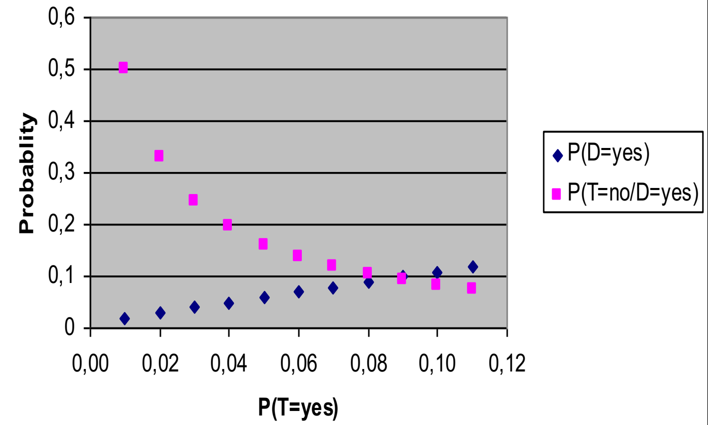


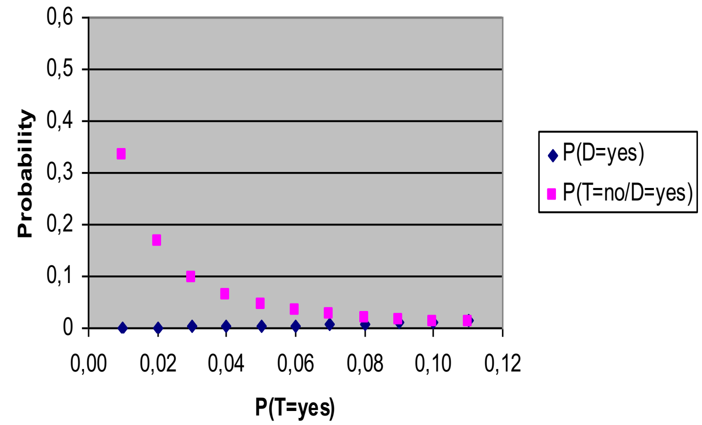


Performances of a single detector with *Sensitivity* = 99% and *Specificity* = 99%

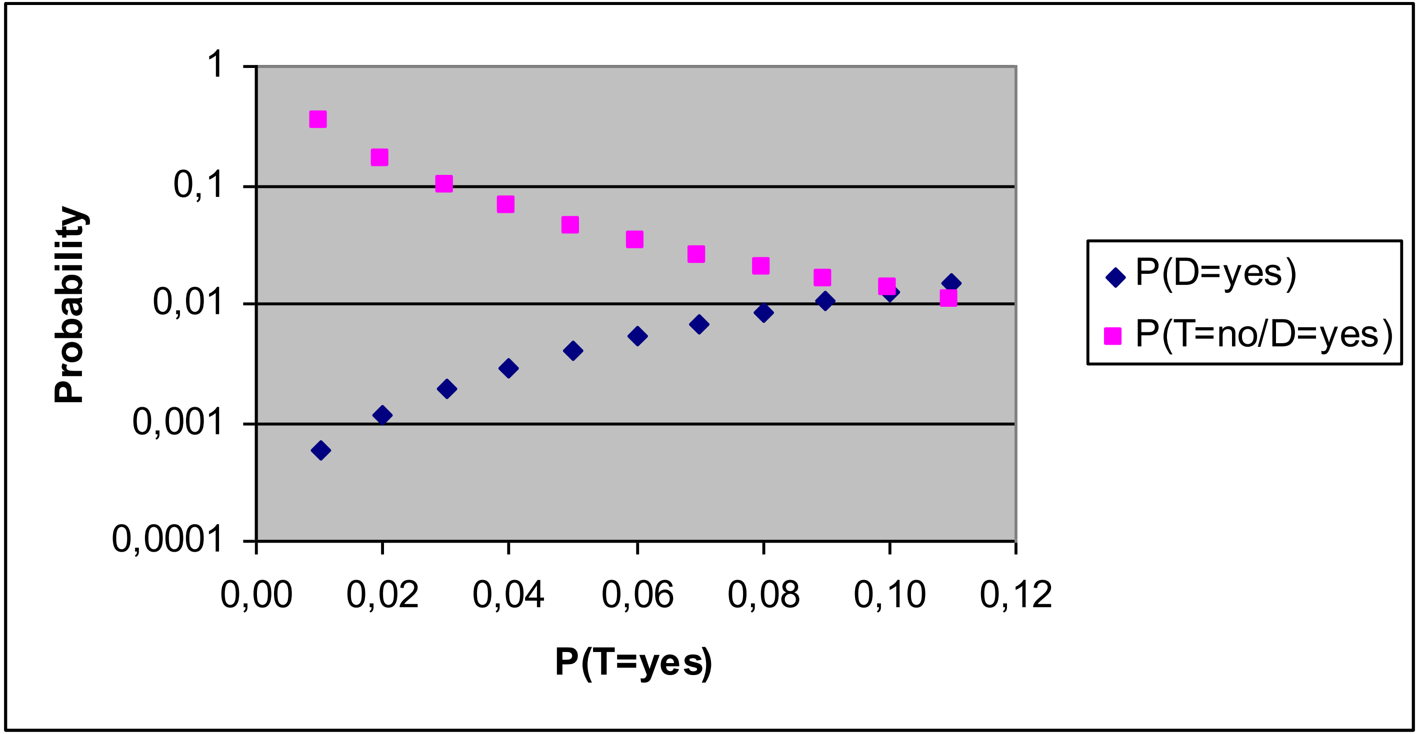
Performances of the "AND" combination of two detectors with:
Sensitivity 99% and 98%
Specificity 99%and 98%

The TPF (*sensitivity*) is decreased (97%) but the field performances of the system for "rare events" are ***better*** than those of a single detector !





Combination of two detectors in “AND” mode → log scale



CONCLUSION

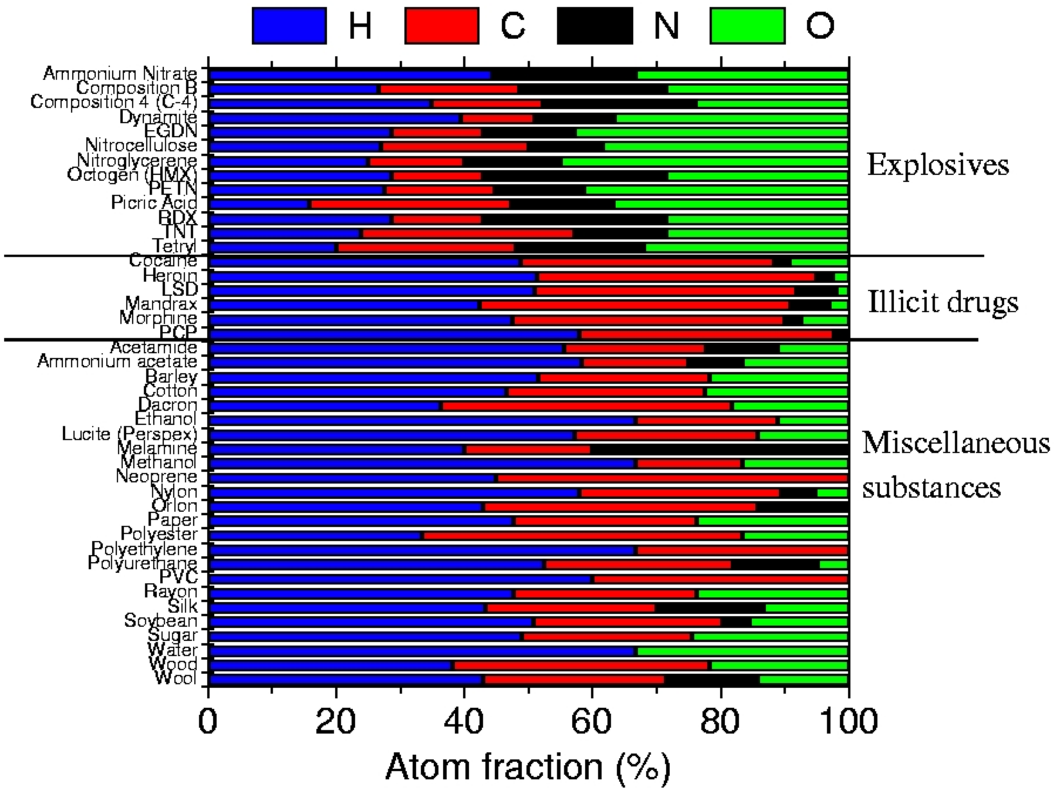
- Evaluation of the performances of any detection system for security screening purposes must take into account the threat scenario
- *Sensitivity* and *specificity* of a detection system are not necessarily the relevant quantities to be considered
- In applications to the detection of very rare events the results based on simple statistical considerations are often misleading
- The use of multiple sensors in “OR” mode generally increases the *sensitivity* but not necessarily the “field performances” of the combined system → largely non-orthogonal sensors give worse “field performances” than a single component of the system
- The use of multiple sensors in “AND” mode while decreasing the overall sensitivity of the system results in a remarkable improvement of the “field performances” of the combined system, in particular when dealing with the detection of very rare events (like in most security applications)


BORD
BORDer Control Points
This equipment is part of a project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement Nº653323.

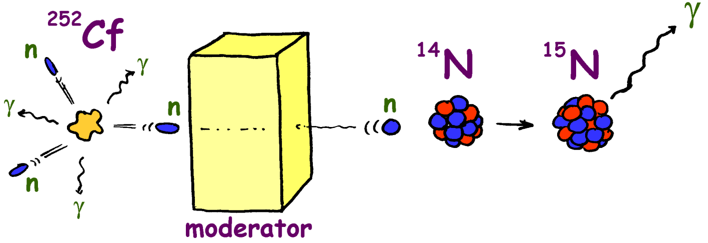
THANK YOU

BACKUP

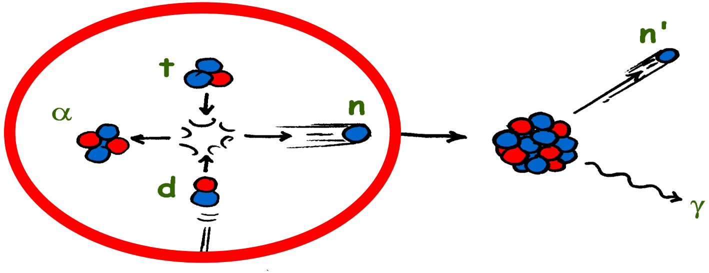
Chemical composition of different materials



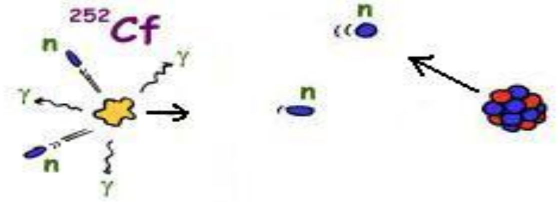
Neutron induced reactions



Thermal neutron capture



Inelastic scattering



Backscattering

Free neutrons

- While bound neutrons in stable nuclei are stable, free neutrons are unstable; they undergo beta decay with a lifetime of just under 15 minutes

$$n \rightarrow p + e^- + \bar{\nu}$$

τ_n= 885.7 ± 0.8 s