Neutron Detection: Principles, Methods, Issues (and Tips)

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Summary

- Introduction
- Neutron sources
- Neutron-Matter Interactions (X-sec)
- Simulation of the Neutrons behaviour in a CMNS experiment
- Neutron Detection in CMNS experiments
- An "ideal" CMNS experiment to detect neutrons
- Conclusion

INTRODUCTION

- The detection of 2.5 MeV neutrons from DD nuclear reactions produced by *“Electrochemically Induced Nuclear Fusion of Deuterium“* claimed for the first time in 1989 (Fleischmann and Pons) → Cold Fusion Experiments (CF).
- In the early period of CF problems to replicate the experiments.
- In the last twenty years the *actual* emission of neutrons from CF phenomena is a matter of discussion among the scientists *(which yield and energy?, how are they produced?).*
- Several claim for neutron emission: different methods, neutron energies, neutron emission rate and lasting time, etc.→ Different theoretical ideas.
- Some authors looking for neutronless nuclear reactions
- Recent claim for measuring 14 MeV neutron (?)
- What else?
- Is it possible to state *unambiguously* whether (or not) neutrons are *actually* emitted from “cold fusion”?

Neutron Sources

- Neutrons are neutral particles forming the nucleus together with protons. Discovered in 1932 by Chadwick *(Fermi experiments in Via Panisperna!! Here around!!)*
- No charge →Easily interacts with matter (Neutrons used as *"probe"* in matter).
- Neutrons do not exist free because decay after 13 min.
- Neutrons are produced by nuclear reactions:

$D+D \rightarrow n + {}^3He + (Q= 3.27\ MeV)$

$D+T \rightarrow n + {}^4He + (Q=14.1\ MeV)$

${}^4He + {}^9Be \rightarrow n + {}^{12}C\ (Q = 5.7\ MeV)$

$\gamma\ (2.76\ MeV) + {}^9Be \rightarrow n + {}^8Be$

Neutrons cannot be accelerate, they loose energy when interacting with matter

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Neutron-Matter Interactions

- The neutron-matter interaction can be described by means of the *cross-section (X-sec)* which, for a nucleus in a given initial state, *depends upon the energy of the incoming neutron*.
- The X-sec *is not a probability but an area*, it is measured in *barn* (1 barn = 10^{-24} cm^2).
- Different types of *"microscopic"* cross-sections (σ_j),

  for the various n-nucleus interaction →**Total** ***Microscopic*** *X*-sec: $\sigma_{Tot} = \sum_j \sigma_j$
- ***Macroscopic*** *X*-sec : $\Sigma_{Tot} = N * \sigma_{Tot}$.
- A beam of monoenergetic neutrons is absorbed as: $I(x)=I_0\exp(-\Sigma_{Tot}x)$ (the inverse of the total cross section is the *"mean free path", $\lambda = 1/\Sigma_{Tot}$).*

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Cross Sections

- *Two* broad families of X-sec:
  a) elastic scattering; b) NON-elastic scattering.
- The basic difference between the two families is in the *neutron energy necessary to occur*.
- Roughly speaking, for ***heavy*** *nuclei* (e.g. Au, Pb, U etc.) at **energy < 0.1 MeV** the main *n-nucleus* interaction is the **elastic scattering** (e.s.)
- For ***light*** *nuclei* (H, D, Li, Al, etc.) the threshold for (e.s.) is shifted toward **higher energy (> 0.5 MeV)**. The elastic scattering is typically almost constant over a wide energy range (e.g. H, up to 100 MeV).
- As soon as the neutron energy increases and reaches at least that of the *first exited level* of the target nucleus (> 5-6 MeV), inelastic scattering as well as other reactions can occur.
- At low energy → Radiative capture, (n,γ) reactions.
- *In condensed matter X-sec and nuclear process can be affected by the "many" nuclei.*

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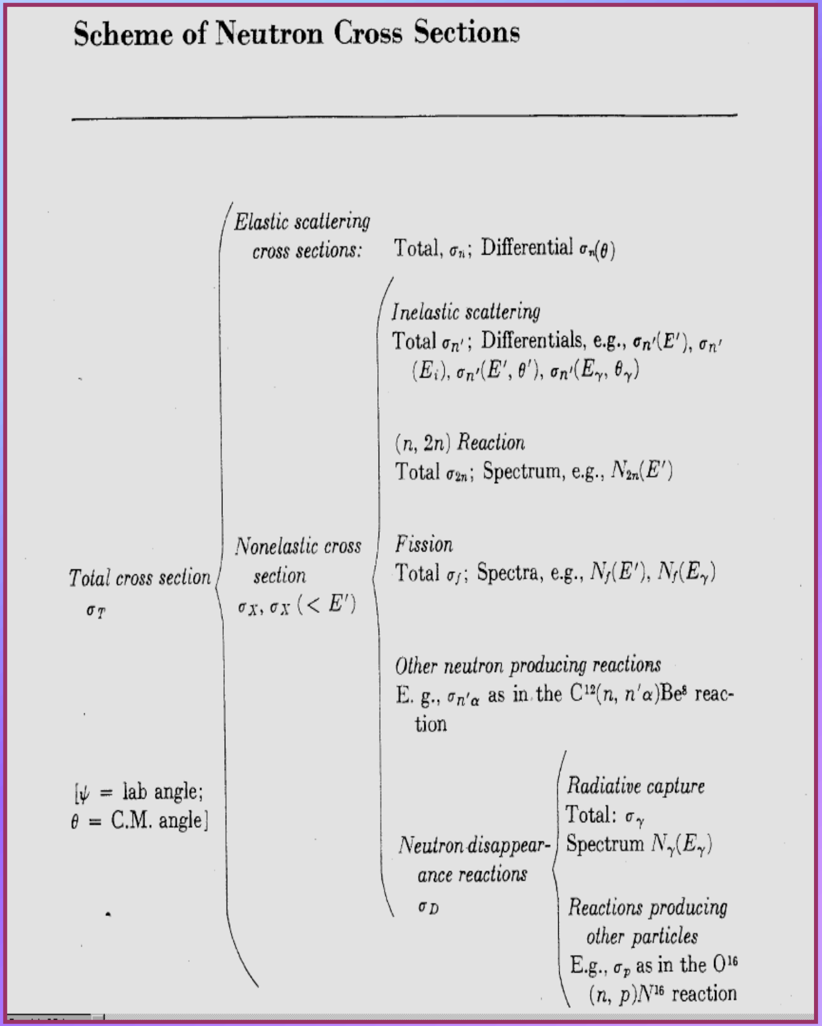
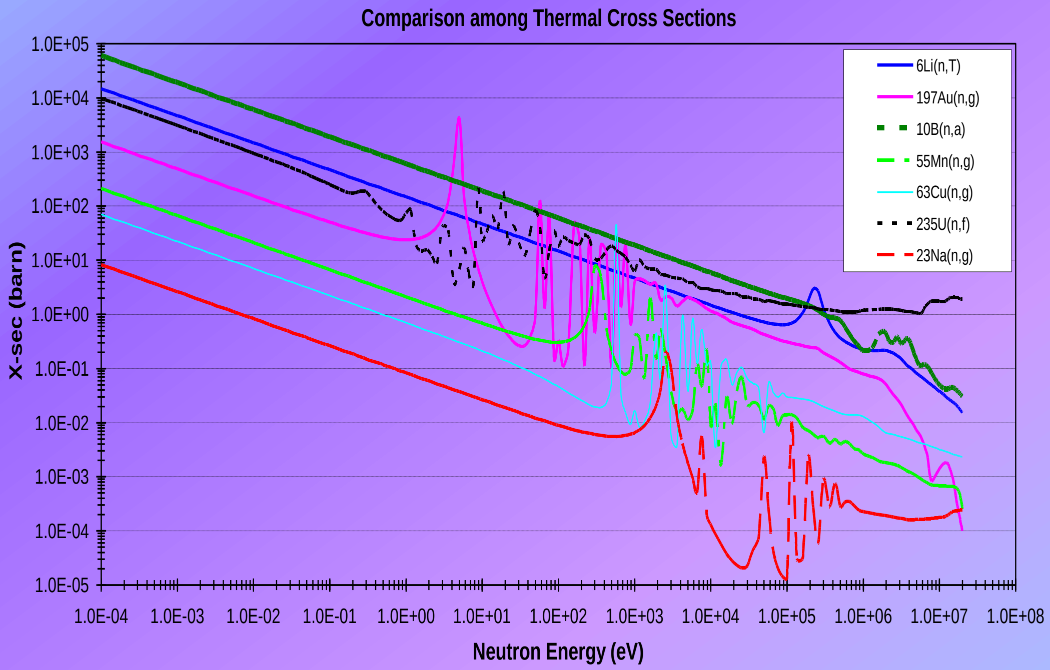
X−Sec



Scheme of Neutron Cross Sections

- *Total cross section* σ_T
  - *Elastic scattering cross sections:* Total, σ_n; Differential $\sigma_n(\theta)$
  - *Nonelastic cross section* $\sigma_X, \sigma_X\,(< E')$
    - *Inelastic scattering*
      Total $\sigma_{n'}$; Differentials, e.g., $\sigma_{n'}(E')$, $\sigma_{n'}(E_i)$, $\sigma_{n'}(E', \theta')$, $\sigma_{n'}(E_\gamma, \theta_\gamma)$
    - *(n, 2n) Reaction*
      Total σ_{2n}; Spectrum, e.g., $N_{2n}(E')$
    - *Fission*
      Total σ_f; Spectra, e.g., $N_f(E')$, $N_f(E_\gamma)$
    - *Other neutron producing reactions*
      E. g., $\sigma_{n'\alpha}$ as in the $C^{12}(n, n'\alpha)Be^8$ reaction
    - *Neutron disappearance reactions* σ_D
      - *Radiative capture*
        Total: σ_γ
        Spectrum $N_\gamma(E_\gamma)$
      - *Reactions producing other particles*
        E.g., σ_p as in the $O^{16}(n, p)N^{16}$ reaction

[ψ = lab angle;
θ = C.M. angle]



- At low energy X−sec much higher than X−sec at high energy (*At low (thermal) energy, neutrons move slowly so, compared to "fast" neutrons, they need a longer time to cross a nucleus. The probability to be captured is thus higher for thermal neutrons than for fast neutrons (radiative capture).*

Neutron Slowing-down

- Neutrons always slow-down when moving in matter.
- Elastic scattering is very common (and constant) at all energies.
- The *energy loss per elastic collision* depends upon the *atomic mass A* of the target nucleus:

$$\frac{E'-E}{E} = -\frac{\alpha}{2}(1-\mu^*)$$

where

$$\alpha = \frac{4A}{(A+1)^2}$$

μ^* is the scattering cosine in the C.M. frame (isotropic)

- **Light materials are efficient neutron moderators.**
- The average cosine of the *scattering angle (in the lab. frame) is $\mu=(2/3)A$* (scattering forward peaked for small A).
- **Heavy nuclei are not efficient moderators,** the scattering is almost isotropic even in the Lab. Frame (C.M. in the nucleus!)

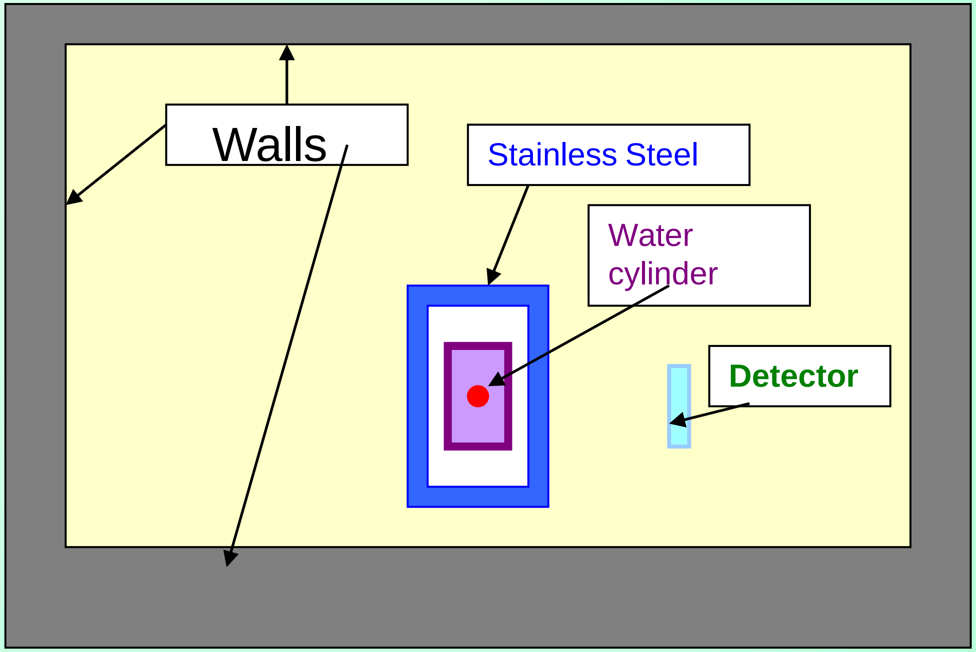
Prompt and Delayed Gamma-Rays

- ✓ Any n-nucleus interaction leaves the nucleus in an excited level from which it decays by emitting gammas.
- ✓ PROMPT GAMMAS are emitted within *10^{-13} sec* and are **always** associated with the neutrons moving in the matter. *Prompt gammas produced at all neutron energies !!*
- ✓ Prompt gamma-rays energy depending upon neutron energy. Typical lines are measurable for each isotope (e.g. *2.2 MeV from H*) and can be up to 10-15 MeV.
- ✓ Prompt gammas responsible for the γ-adsorbed dose!
- ✓ *Neutron induced radioactivity:* Nuclear reactions *A(n,x)B* leave the reaction products in excited levels from which they decay emitting particles (α, β etc.) with variable Half-Life as well as gammas (*delayed γ-emission)* → *Artificial RADIOACTIVITY.*

Neutrons simulation in CMNS Exp.

- A "typical" assembly for CMNS experiment *simulated* using Monte Carlo Code MCNP-5
- The main properties of the system are investigated. This can help in planning neutron measurement in a CMNS experiment
- *DD neutron source (2.5 MeV): Burst emission? Long lasting?*

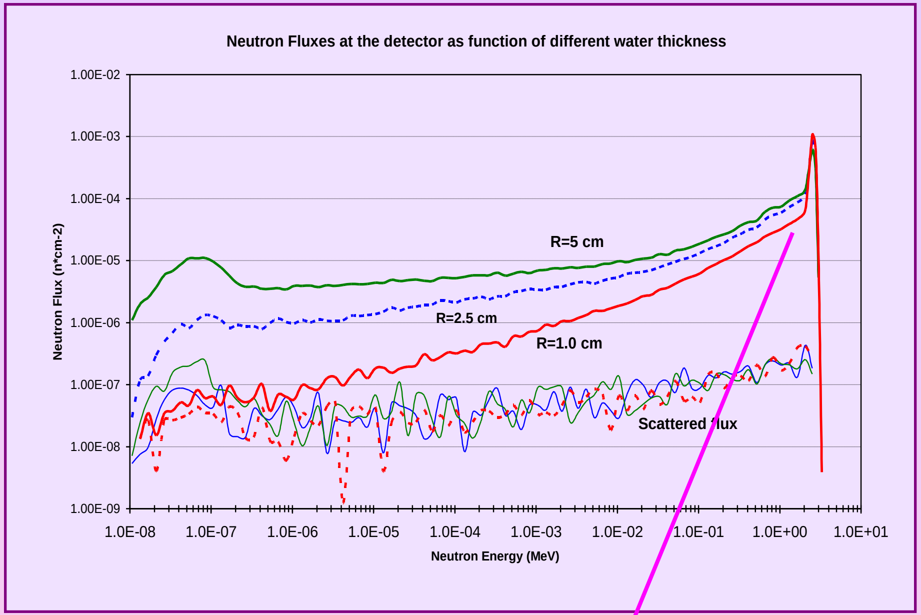
<u>It does No matter for transport calculation!</u>

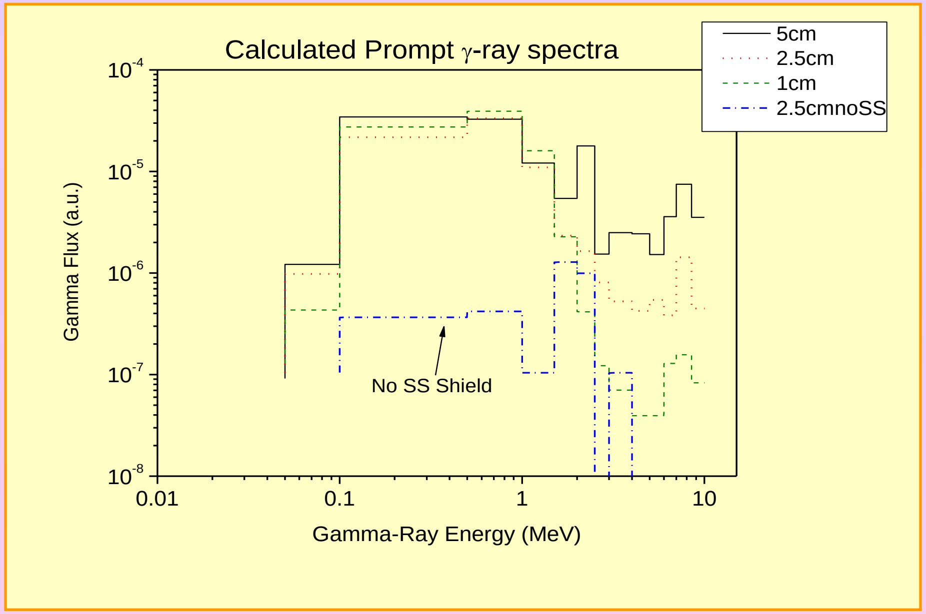


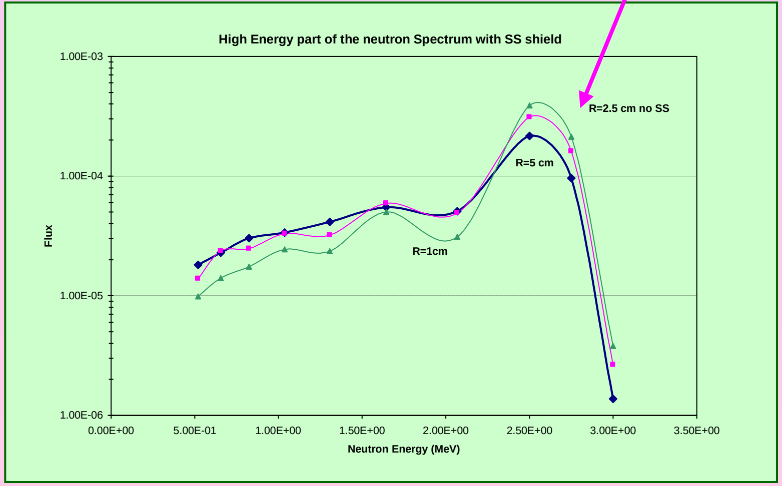
<u>The calculation model:</u>

- *Glass of water with variable Radius where DD "cold fusion" is produced*
- *Stainless Steel covering the system*
- *Detector in fixed position*

Calculation Results







- n-spectra depending upon water thickness (→ thermal peak).
- Neutron “background” almost constant.
- γ-spectra depending on materials
- Output of simulation→ n detection

Neutron Detection

- Neutrons detected using *indirect methods* → n converted into something else in a *converting medium* (The latter not necessarily is the detector).
- Two broad class of detectors:

1- *Active Detectors*

2- *Passive Detectors*

Both n and γ (prompt and delayed) can be measured in a CMNS experiments.

The simultaneous use of Active and Passive detectors can lead to "unambiguous " neutron detection in a CMNS experiment.

The neutron and gamma energy spectra can be recorded as well (good statistics is mandatory)

Active Detectors

- *Active detectors* necessitate of H.V. to operate and produce electrical signals (pulses or current) that can be recorded for on-line/off-line analysis.
- Among the many types of available **active neutron detectors**, the most suitable can be: Fission chambers (FC) (^{235}U, ^{239}P, ^{238}U etc.), BF_3 and He-3 tube, ^{6}Li covered detectors (Si-diode or diamond), Scintillators (NE-213 or NE-422).
- *Active gamma detectors*: Scintillators, Ionization and/or Proportional chambers, Geiger-Muller (GM) tube
- Due to the unpredictable intensity and type of the neutron emission (Burst(s)? Long lasting?), operation in *Pulse mode* seems more effective.

NOTE: Active detectors are sensitive to E.M. noises [caution when operating under EM or MF. Shielding required (Aluminum, μ-metal (Ni-Mo annealed) oy].

Active Detectors-2

- All active detectors to be located “around” the neutron source, but some can be introduced inside the aqueous solution, *provided they are waterproof* (e.g. FC), *to increase* the incoming neutron flux.
- *Thermal detectors→ Response enhanced by neutron “moderators”*

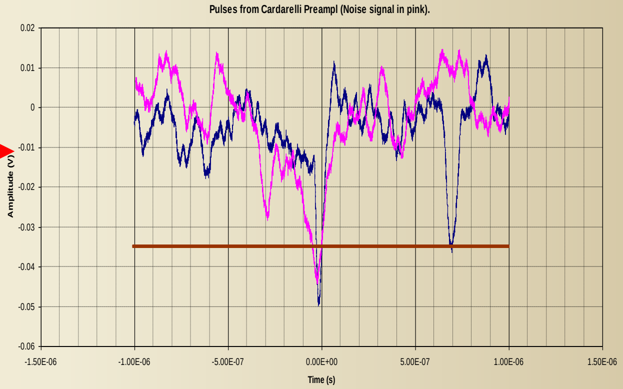
NOTES: *1)* GM tube with mylar window as well as large Si-diode suitable for in-water charged particles detection too.

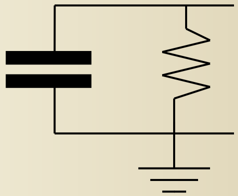
2) Instrumentation borrowed from health physics groups usually is not very suitable for measurements because of : *low sensitivity, large errors, slow electronics.*

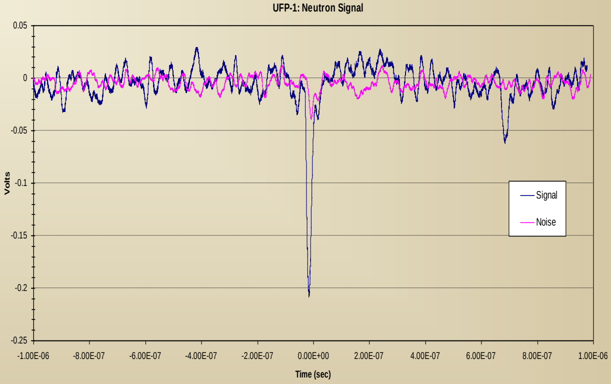
3) Some instruments are working in current mode and need long integration time. Not recommended for “Pulsed” sources.

Active Detectors-3

- The use of active detectors requires a deep analysis of the noises and an accurate measurement of the background (to be repeated also after the measurement is over)
- Every active detector can be regarded as a Capacitor in Parallel to a Resistor (e.g. equivalent circuit for FC. or Ion. Chamber), so impedance adaptation is fundamental to avoid trivial mistakes (e.g reflections).
- High Frequency → more problems, variable impedance


Pulses from Cardarelli Preampl (Noise signal in pink).




UFP-1: Neutron Signal

Active Detecors-4

Tips:

- ✓ Use cables of the proper impedance for connection to amplifiers, discriminators, scalers, MCA etc.
- ✓ **Check noises** (some detectors are sensitive not only to EM noises, but also to mechanical and acoustic noises!).
- ✓ Threshold discriminators can help in reducing noises count-rate
- ✓ Remember to switch-off mobile phones (2GHz signals!!). Use a wide band scope to see High frequency noises!!
- ✓ High frequency noises very difficult to eliminate.
- ✓ A trick to reduce high count rate due to burst of neutrons: use fast detectors (e.g. scintillators) and slow down neutrons using moderator! (few cm).
- ✓ High count rate → pile-up effects → peak summing→ wrong spectrum!

Passive detectors

- Some passive detectors can be very helpful in a CMNS experiment because their response can be attributed to neutrons and gammas with a very low level of uncertainty.
- Among the others ***Activation foils*** (AF) seems the more reliable.
- Activation foils uses (n,x) nuclear reactions. *Thermal* and *epithermal* (n,γ) reactions have large cross sections and activation is relatively easy even at low neutron fluence.
- The response of AF can be enhanced by slowing-down neutrons using moderators (e.g. polyethylene, PMMA etc.).
- *Irradiation to be repeated whether necessary (to demonstrate the reproducibility of CMNS phenomena).*

Passive detectors-2

- *Some useful activation reactions for CMNS experiments:*

Reaction	**Half-life**	**γ (keV)**
^{115}In(n,g)^{116}In	56 min	1097/1293
^{197}Au(n,g)^{198}Au	2.70 d	412
^{164}Dy(n,g)^{165}Dy	2.33 h	β^- (2 MeV)
U/Pu(n,f)		

The reactions to be effective should have high X-sec and short half-life.

- ❖ A.F. will produce a clear and unambiguous evidence for neutron production (high purity materials to be used as foils).
- ❖ For each AF we can calculate the *lower limit* for the neutron emission that can be measured *(detection limit→ proper quantity).*
- ❖ Low activated foils can be counted in a *"low background" laboratory* (e.g. Gran Sasso).
- ❖ The background to be measured before and after the irradiation, using foils of the same stock.
- ❖ Calibration can be performed using calibrated neutron sources

Passive detectors-3

NOTE: A.F. can also be used if charged particles are produced in the aqueous solution. In this case (p,x), (d,x), (α,x) etc. reactions can be measured in many materials (^{7}Li, ^{9}Be, B, F, Al, V, Fe, Ca etc.). The threshold energy is > 4-5 MeV.

- *The main draw-back is the range of charged particles in water (few microns)*
- *AF can be used in parallel with CR-39.*
- *CR-39 has been used so far (many criticism).*
- *CR-39 response can be influenced by many factors while AF are insensitive to almost all of them.*

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An “Ideal” CMNS Experiment

- After more than 20 years time has came for unambiguous measurement of neutrons (Yes/No neutrons) in a CMNS experiment.
- A series of experiments can be designed to meet this goal.
- Many problems must be faced and the instrumentation set-up must consider several possibilities e.g.: *burst or continuous neutrons emission(?), high/low emission rate (?), energy different from 2.5 MeV (?).*
- *The instrumentation must be redundant in order to get different types of unambiguous responses. The basic idea is, at least, to duplicate any measured quantity.*
- *The different methods must be independent*

An Ideal CMNS Experiment-2

- ✓ The detectors to be used can be F.C., BF_3, He-3, Scintillators, Ion. Chamb., A.F., CR-39.
- ✓ The goal is to detect both *n* and *gammas*, whether possible.
- ✓ The detectors should operate in pulse mode.
- ✓ Experiment to be reproduced (at least 2-3 times) for activation purposes and asses reproducibility.
- ✓ The used active detectors must have large volume/mass to increase the sensitivity (background!!→ shielding).
- ✓ *The activation analysis of the electrode (Palladium or other material) to be considered as well.*

(n,x) Reactions in Pd

X. Kong et al. / Applied Radiation and Isotopes 50 (1999) 361–364

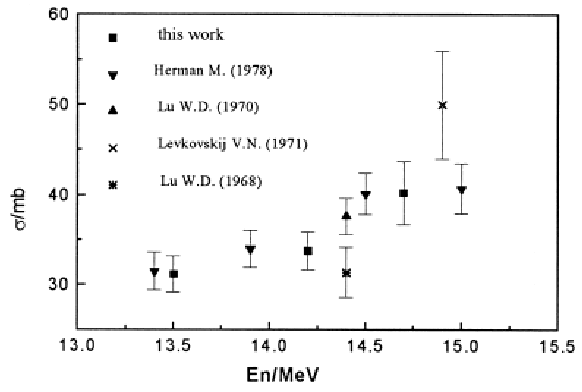
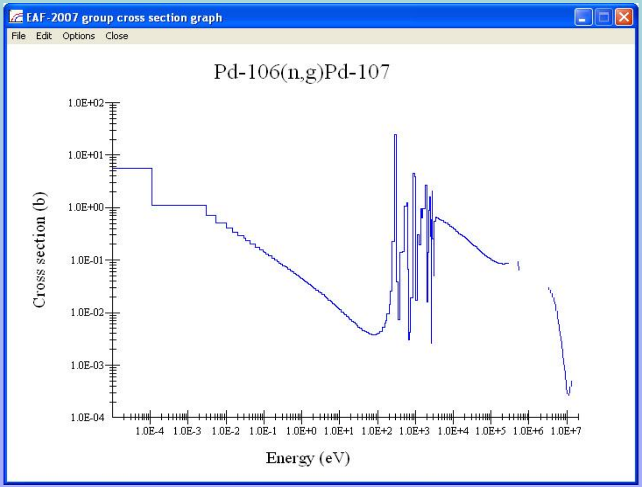


Fig. 1. Cross section of ^{105}Pd(n, p)^{105}Rh reaction.

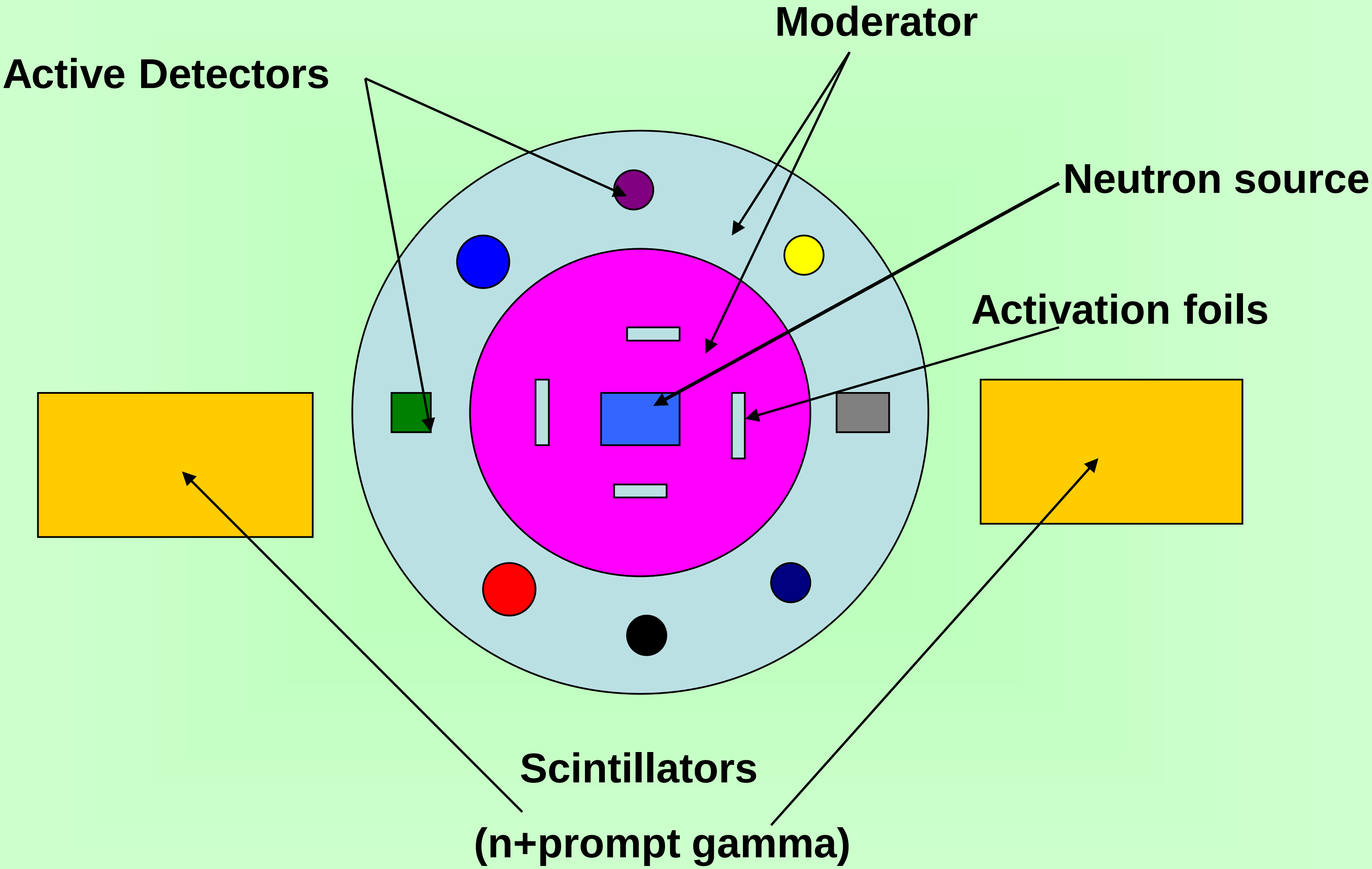


Isotopes	*W%*	*Reaction*
102	1.02	(n,p) (n,2n)
104	11.14	(n,γ) (n,p)
105	22.33	(n,γ) (n,p)
106	27.33	(n,γ) (n,p)(n,α)
108	26.46	(n,γ)(n,p)(n,2n) (n,np) (n,α)
110	11.72	(n,γ) (n,2n) (n,α)

Small X-sec, low background laboratory to be considered for activation measurement

(n,γ) reaction to be considered

Lay-out of the Experimental set-up



Moderator

Active Detectors

Neutron source

Activation foils

Scintillators

(n+prompt gamma)

Conclusions

- The neutron emission from a CMNS experiment can be measured using a set of different active/passive detectors. Reproducibility is mandatory (Detectors are not black-boxes!!)
- Calibration, noise analysis and background measurement required for each type of detector.
- The confirmation of the neutron production will be obtained by “overlapping” and matching the response of the single detectors.
- Data from activation foils and activation analysis of the Pd electrode are critical for unambiguous claim of the results.
- ***The experiments will be succesful even if they will demonstrate that neutrons are not emitted!!***

THANK YOU !!