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

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Abstract. The production and detection of neutrons in the so called "cold fusion" phenomena is claimed since the first announcement by Fleischmann and Pons in 1989. In the last twenty years the same claim has been made by other authors despite they were operating under different experimental conditions. However, most of the scientific community is yet sceptic about the actual emission of neutrons from events that in a more general statement are known as "low energy nuclear reactions in condensed matter" (CMNS) and the methods adopted by the various authors are often subjected to several criticisms. Indeed CMNS phenomena are rather complex and relate with several different subjects so synergy among various experts is necessary. Among these subjects, neutron detections requires a particular care and expertise because the measurements are carried out with a very low signal to noise ratio. In this paper a very brief review of the main physical laws and basic detection principles for neutrons are addressed. It is not in the author's intention to investigate whether or not neutrons are actually emitted in CMNS phenomena, however, some tips that could allow to unambiguous measurement of neutrons from a CMNS type experiment will be addressed too.

1 Introduction

Since the first announcement by Fleischmann and Pons [1] and just after by Jones [2] and Scaramuzzi [3] who claimed the production and detection of 2.5 MeV neutrons from DD nuclear reactions produced by *"Electrochemically Induced Nuclear Fusion of Deuterium"*, the actual emission of neutrons from the so called *"cold fusion"* phenomena is a matter of discussion among the scientists.
In the last twenty years a great debate has arisen to establish whether or not neutrons are actually emitted and at which energy. Many authors attempted the neutron detection under experimental conditions often far different [4,5] from these discussed in [1-3]. The results were often contradictory and in some cases claim for detecting neutrons of higher energy were made [6,7]. On the other hands, some authors considering the "strange" and not reproducible results, suggested that from the so called *"low energy nuclear reactions in condensed matter"* (CMNS) phenomena, neutrons are not produced. Following these authors, the observed "anomalous" heat production is to be ascribed to nuclear reactions which led to the production of charged particles. However, recently in a attempt to measure such charged products some authors claimed they found 14 MeV neutrons [8].
The above short story of "cold fusion" phenomena is far to be complete, but clearly points out that the question of whether neutrons are actually produced and at which energy is still open. More debating is the question "how" neutrons are produced. Even within the community working on CMNS there are different ideas. Indeed CMNS phenomena are rather complex and relate with several different subjects so synergy among them is necessary. Among these subjects, neutron detections requires a particular care and expertise because the measurements are carried out with a very low signal to noise ratio. It is not in the scope of this paper to review the various experiments nor to put specific questions or criticism to any of the papers available in the literature and reporting about neutron measurements from CMNS experiments. The present paper represents an attempt to clarify some basic aspects about the neutron physics and detection.
Last, but not least, in the author's opinion time has came to try to measure neutrons in a CMNS experiment (if any) in unambiguous manner. This can be attained in a series of experiments where the detection of neutrons is detailed designed, carefully performed and repeated.

2 Neutron Sources

The neutron was discovered in 1932 by Chadwick and since the early days of its discovery the "strange and intriguing" properties of the neutron were studied with great interest by the physicists.
Neutrons can be produced by nuclear reactions. There are a number of reactions routinely used for producing neutrons, among them typical sources of neutrons are :

$D+D \rightarrow n + {}^3He + (Q= \ \ MeV)$; $D+T \rightarrow n + {}^4He + (Q=14.1\ MeV)$; ${}^4He + {}^9Be \rightarrow n + {}^{12}C$ $(Q = 5.7\ MeV)$
$\gamma\ (2.76 MeV) + {}^9Be \rightarrow n + {}^8Be$

Since neutrons are neutral they are not sensitive to the coulomb barrier of the nucleus and thus can easily interact with them. The type and probability of interaction can be foreseen if the initial state of the nucleus and the energy of the neutron is known. Neutrons cannot be accelerate since they are neutral, but always they loose energy as soon as they interact with matter. This means that if *monoenergetic* neutrons of energy E_0 are produced, after moving in the surrounding material the neutrons will have a continuous spectrum ranging from the initial energy E_0 down to the thermal one (E_{th}).

3 Neutron Interactions

The neutron-matter interaction is depending upon the so-called cross-sections. The latter, for a given nucleus in a known initial state, depends upon the energy of the incoming neutron. The concept of "cross section" is familiar in the nuclear and atomic physics and relates with the "probability of occurrence of a certain process when a particle is interacting with another particle or nucleus. Strictly speaking the cross-section is not a probability but an area since it is measured in barn (1 barn = 10^{-24} cm^2). Physically the cross-section can be regarded as the area seen by the projectile when approaching the nucleus and to which "actually" it interact. The larger the area the larger the "probability" (cross section, σ) of a certain interaction. This concept can easily be explained by quantum physics if the incoming particle (the neutron in our case) is assumed to be a wave of probability [9,10]. As a consequence of the neutron-nucleus interaction there are many different "final" states, each one characterized by some "typical" reaction products. The j-th final state will have cross section σ_j, so we can define the total cross-section as the sum of the above different "final" states : $\sigma_{Tot} = \Sigma_j \sigma_j$. In this sense, if we consider the ratio $f_j = \sigma_j / \sigma_{Tot}$, f_j is the probability of having the reaction of type j.
σ_{Tot} is the so-called *microscopic* total cross-section which must not be confused with the *macroscopic* cross-section for a given material defined as $\Sigma = \sigma_{Tot}$*N where N is the number of nuclei per unit volume. Σ is measured in cm^{-1} and $L=1/\Sigma$ (cm) is the *mean free path* and gives the mean distance travelled in a medium by a neutron of a energy E before to produce an interaction.
The total cross-section can be divided into two broad families, the *elastic scattering* and the *NON-elastic* scattering cross sections, respectively. The latter comprises several different types of cross sections (Inelastic scattering, compound nucleus reactions or radiative capture, fission, charged product reactions, spallation, stripping etc.), each representing a specific type of n-nucleus interaction. The basic difference between these two broad families is in the neutron energy. Roughly speaking for energy lower than a 0.1 MeV the n-nucleus interaction is an elastic scattering. As soon as the neutron energy increases and reaches at least that of the first exited level of the target nucleus, inelastic scattering (that is one of the above mentioned reactions) can occur, each one with a probability defined by f_j.
The cross sections of the various nuclides as function of the neutron energy are available in a number of nuclear data libraries (e.g.[11]). From the analysis of some typical neutron cross-sections versus the neutron energy (Fig. 1), it can be seen that they behave in a rather standard mode but for a fixed neutron energy E_n the cross section value can be very different, depending upon the nucleus. Three different energy regions can be observed:
1) *the* $1/\sqrt{E_n}$ *or 1/v region* (v being the neutron velocity), in the very low energy part and up to 1-2 eV);
2) *the resonance region* from the eV region and up to ~10 keV;
3) *the high energy region* (>0.1 MeV).

The cross sections values at the thermal energy E_{th} (σ_{th}, where E_{th} = 0.025 eV at T=300°K) depends upon the isotopes and can change of many order of magnitude. The σ_{th} values varies from 10^{-3} b for D and O up to 10^6 b for ^{135}Xe. At low (thermal) energy, the neutrons move slowly so, compared to "fast" neutrons they need a longer time to cross a nucleus so the probability to be captured is higher for thermal neutrons than for the fast ones. On the other hands, the scattering cross-section at the thermal energy results of the same order of magnitude for all the nuclides. The latter fact can be intuitively explained considering the scattering between the neutron and the nucleus similar to that occurring between two rigid spheres. In this case the scattering cross section σ_s is proportional to the nucleus cross section area πR^2, R being the nucleus radius which in turn is given by R= $*A^{1/3}$ where A is the atomic mass and $r_0 \approx 1.5*10^{-13}$ cm. Indeed, the elastic scattering cross section is slightly varying with the neutron energy for most of the nuclei.
The neutron cross section behaviour can be explained in a rigorous mode by quantum mechanics (e.g. [9]).

3.1 Prompt and delayed Gamma-Rays

A peculiar aspect of the neutron-matter interaction is the production of the so called "*mixed n-γ field*" in which the neutrons and gammas are simultaneously present. The measurement of this mixed field represents a possible approach to demonstrate the neutron production in physical phenomena. Since gammas are *always* produced by

neutrons, if neutrons are measured but no gammas are observed (both during and after the neutron emission), caution is mandatory before to claim that a neutron emission was actually observed.
It is fundamental to distinguish between two classes of gammas emitted from a medium interacting with neutrons: *a)* prompt gamma-rays; *b)* delayed (or activation) gamma rays.
The prompt gamma-rays are those emitted in "real-time" whilst the neutrons are moving and producing n-nucleus interaction (e.g. inelastic scattering). The n-interactions excite the nuclei which decay by emitting gammas in a very short time (10^{-14} sec, so the name *prompt*). The prompt gamma-rays energy spectrum range from a few hundred of keV up to 15 MeV and even more, depending upon the nucleus.

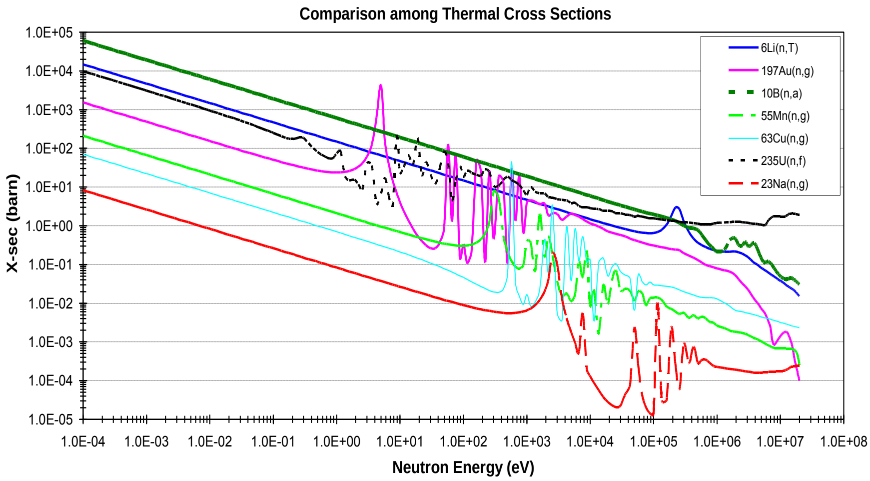

Fig. 1. - Cross-section versus neutron energy for some materials.

It is important to stress that the prompt gamma-ray emission is observed at any neutron energy and the energy of the emitted gammas can be neutron energy dependent. The latter property is used for performing elemental analysis by prompt gamma ray neutron activation analysis (PGNAA). PGNAA can also be used to measure the intensity and the energy (by analyzing the gamma–ray lines) of the neutron source.
The *delayed gamma-rays* are emitted by the excited states of the neutron activated materials which in turn are produced by the (n,x) nuclear reactions (here x means, n', p, d, α etc.). These excited states decay by alphas and/or betas (some time directly by gammas, this is the *isomeric transition*) but the daughter nuclei are still exited and usually decay by emitting one or more gammas of energy ranging from a few tens of keV up to 3 (or more) MeV. The delay time also known as decay time, can be very variable. Again from the produced gamma-ray lines it is possible to know the energy of the neutron source and also its intensity. The detection of the "activation" products is the most direct and safe method to demonstrate that neutrons have been actually produced.
The prompt as well as the delayed gamma-ray emission can be foreseen for each nuclide provided that the energy of the neutron is known. Libraries of nuclear data are available for this purpose (e.g.[11]).

4 Neutron Detection

The detection of neutrons can be attained by considering their interactions with matter. As already explained the n-matter interaction depends upon the neutron energy so we must expect that there are different type of detectors at different neutron energies. Always a neutron is detected using an in-direct method, that is thanks to the conversion of a neutron into something else, so we will detect gammas or charged particles. The conversion process is produced inside the "detecting" medium which not necessarily is the detector.
Among the many detectors developed so far to measure the neutrons (see e.g. [12]), we can distinguish two broad families: *a)* active detectors, *b)* passive detector.
Are considered active the detectors that need an external bias for operating (e.g. fission chambers, scintillators, ionization chambers, Geiger-Muller etc.). It is also important to distinguish between detectors operating in pulse or in current mode. The first type is recommended for sources emitting burst of neutrons. The current mode is suggested for long lasting neutron emissions but also for high (and some time low) intensity sources. When close to the neutron source and or to the detector are present sources of EM radiation caution is necessary and shielding is strongly suggested. Proper shielding is also requested for the cables that can act as antenna. Screened or super-screened cable are recommended.
The passive detectors instead, do not need any external biasing (e.g. thermoluminescent detectors, activation foils, CR-39 etc.) even if internal junctions are possible. The use of passive detectors require other type of cautions specific for each detector. For example, thermoluminescent dosimeters usually do not withstand high temperature

and require an accurate background dose measurement with long lasting exposure. CR-39 must not be exposed to sun or heated as well and must be handled with care since any surface damaging can result in a wrong track. Their response can also be enhanced by using a thin layer of plastic to produce recoil protons or other charged particles.
The most simple detectors to be used are the activation foils for which a few recommendation are mandatory the main being to avoid contamination (to be cleaned before the experiment) or exposition to neutron sources before the experiment.
Basing upon the claimed results, the detection of neutrons in a CMNS experiments consists basically in a short-lasting neutron emission that typically starts suddenly, as a burst. The claimed level of the neutron emission is very variable from a few counts up to many hundreds so pulse detectors seem appropriate although the count rate can be very low. Assuming, as working hypothesis, the neutrons to be emitted from a DD reactions, neutrons will have an energy of about 2.5 MeV so almost all the detectors above mentioned can be used to detect them.
A problem is represented by the need to separate the background from the “true” signal especially if the counts are just a few. Under these circumstances it seems also difficult to perform the spectrometry since the statistics is an important aspect of the latter measurements. The measurement of the background prior the experiment is mandatory, but the background must be also measured after the end of the experiment to verify that no changes in the environments have happened in the meantime. Whether possible the spectrometry of the background radiation must be performed. Both n and γ background must be measured.
Due the many problems envisaged in the past in the CMNS experiments and also accounting for the many criticisms it is suggest to use a redundant array of different type of detectors rather than to use a single detector. The simultaneous signature of the various detectors will guarantee about the neutron (and gamma) emission.
Active detectors such as fission chambers or scintillators of large sensitive volume, seem more appropriate since allow also for the measurement of the time dependent neutron emission that can help in the analysis of the physical problem. To enhance the response of the detectors (e.g. fission chambers, H3-tube, Li-6 covered or coated detectors) the neutrons can be slowed down by using a few centimetres of moderators (e.g. polyethylene) located in front of the detector or all around the neutron source.
Another important point is the simultaneous detection of neutrons and prompt gammas by coupling the neutron detectors with some gamma detectors (in this case γ-spectrometry is also feasible). Some materials such as H, emits typical prompt gamma-rays (2.2 MeV for H) so their detection can be a further and independent proof of the neutron emission.
It ought to be stressed that instrumentation borrowed from the health physicist usually is not recommended for this type of measurements since most of this instrumentation have low sensitivity (and high sensitivity for both type of radiation is needed), are not very fast since usually measure the “level” of radiation and also cover a very large energy and sensitivity range but their response can be too slow.
Another measurement that is always possible is that of the “activation” products due to neutrons emission. In this case some activation foils (e.g. Au, In) can be used. To increase the sensitivity large surfaces and several grams of materials must be used and the foils must wrapped inside a moderator (polyethylene) or can also be introduced in the aqueous solution. To increase the signal to noise ratio the measurements should be carried out in a “low background” laboratory.
If Pd or Ti plates are used as electrodes in a CMNS experiment, it is expected that some (low) activation is also present in these materials. Ti reacts both with fast and thermal neutrons while Pd only with thermal neutrons. Both natural Ti and Pd are a mixture of several isotopes and almost all of them react with neutrons. The characteristic gamma-ray lines can be detected by a spectroscopic apparatus (e.g. using a Germanium detector). A calibration before the experiment is suggested using plates made with the same material and irradiated in a reference neutron flux, in order to study both the γ-ray spectra for a comparison and in case to get a quantitative analysis of the neutron production in the CMNS experiment.

5 Monte Carlo simulation of a CMNS experiment

To better understand the issues to be faced in a CMNS experiment when attempting to measure the neutron emission a simulation of a “typical” experiment was performed by using the Monte Carlo code MCNP.
The model is reported in Fig.2. A glass cylinder (2 mm thick) is filled with water and it is containing a neutron source. The detector is at a fixed distance from the source and the system is housed in a concrete box with walls and roof having the same thickness (15 cm) while the floor is more thick (30 cm). The neutron source is at 1m from the floor while the dimensions of the concrete box are 4x4x6 m^3.
By changing the dimensions (radius) of the glass cylinder (and thus the quantity of water contained in it) as well as the energy of the neutron source (DD and DT neutrons), the neutron and gamma spectra in a region simulating the detector and located next to the cylinder (see picture) are calculated. The detector is a cylinder of air and its distance from the centre of the neutron source is kept constant as the cylinder radius changes.

5.1 Results of the simulation

The calculation was performed using two neutron source energies: E_{DD}= 2.5 MeV and E_{DT}=14 MeV. A second calculation was run enveloping the water cylinder in a second cylinder made of stainless steel (SS) 1 cm thick. The SS cylinder in some papers was used as "electromagnetic" shield but the use of shields made of Al or μ-metal, is suggested when using (variable) magnetic fields. This shield will have an impact also on the neutron and gamma emission and must be accounted for.

In Fig. 3 the neutron spectra calculated at the detector position are shown. The calculations were performed for three different radii of the glass cylinder: R= 1.0; 2.5 and 5.0 cm respectively. Fig. 3 shows the effect of the increasing radius on the calculated neutron spectrum at the detector location. As the water thickness increases the neutron spectrum enlarges. For R= 5 cm, the typical tail at the low energy part of the spectrum is visible as well as the thermal peak. It is interesting to note that the neutron background spectrum and intensity do not change very much. For comparison the neutron spectrum due to DT neutrons is also reported.

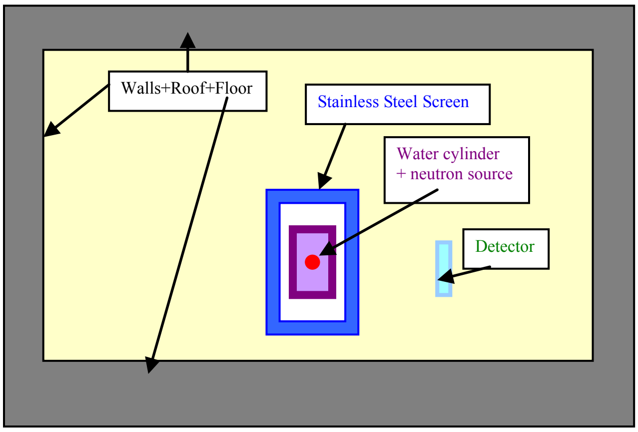

Fig. 2. - MCNP Model of a CMNS experiment

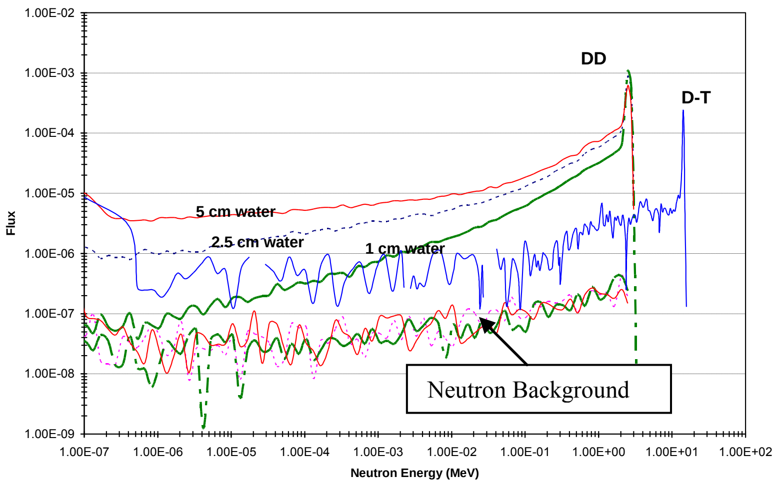

Fig. 3. - Calculated neutron spectra as a function of the Radius R at the detector's position

In Fig. 4 the prompt gamma-ray spectra calculated for the DD source are reported together with the spectrum calculated for the case of the SS cylinder enveloping the neutron source. The effect of higher neutron energy (DT source) on the "prompt" gamma-ray spectrum is shown too. The above results point out several important facts:

a) The neutron spectrum depends upon the neutron source energy and the amount and type of material surrounding it. The background, due to wall return effects, depends mainly on the geometry of the system (source-walls distance).

b) Any material interposed between the neutron source and the detector can affect the "shape" of the neutron spectra as well as will modify the spectrum of the prompt gammas.

c) The "prompt" gamma-ray spectrum depends upon the neutron energy.

d) Walls, roof and floor always contribute to the total response via scattered neutrons (and gammas). A more general statement is that any material and structure surrounding the source affects the detector's response.

6 Tips for unambiguous neutron detection in a CMNS experiment

The above discussion, together with the short notes reported on the neutron detection, allows us to summarize the discussion and to give a few suggestions and tips for unambiguous detection of neutrons that indeed, is what is still requested to a CMNS experiment.

To be unambiguous neutron detection must provide a clear and not questionable signature of the event. For this reason a simple but affordable system is suggested. The detectors should have a large volume to increase the detection efficiency (but also the background is increased), operate in pulse mode and over all be based upon different principia. So fission chambers can be coupled with scintillators as well as with activation foils. Scintillator can simultaneously measure and discriminate neutrons and gammas provided that a proper discriminating electronics is set-up . Calibration is also needed for all the detectors both with respect the energy and whether possible efficiency. The "neutron source" can be enveloped by a moderator in order to slow-dawn neutrons and enhance the response of the used detectors (some scintillators, e.g. NE-422, are sensible to slow neutrons, while NE-213 is sensible to high energy neutrons (> 1 MeV)). Since the neutron emission is expected in the range of some MeV a few centimetres (3-5) of polyethylene can be sufficient. Activation of ^{197}Au, ^{109}Ag or ^{113}In which are sensible to thermal neutrons and have a relative short activation time is possible. The use of short life nuclides is suggested for activation since the expected neutron fluences are not too high.

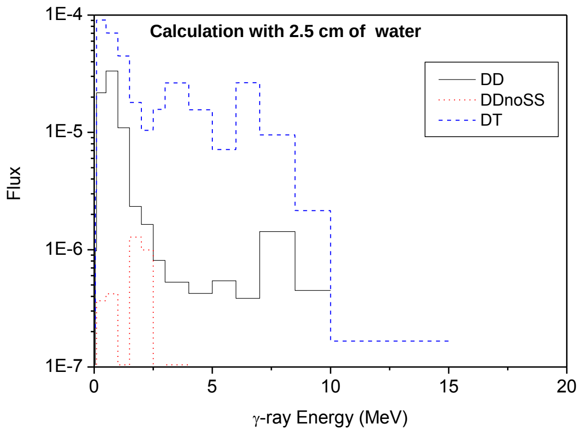

Fig. 4. - Prompt gamma-ray spectra calculated for a DD neutron source also enveloped in a SS shield. The prompt gamma-ray spectrum obtained with DT neutrons is also reported for comparison.

A detector based on ^{109}Ag can be particularly suited for a CMNS experiment since it allows for neutron activation to be detected, its short half-live (about 24 sec) β-decay can be efficiently measured by a beta counter (e.g. a simple Geiger-Muller tube) so following the decay curve. This instrument will give a double, independent and unambiguous signature of a neutron activation. The advantage is that the activation is not influenced by any possible external EM noise or field while the measured activation will follow a well known decay curve.

Last, but not least, the measurements must be repeated and the results reproducible.

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