CHARACTERIZATION OF A BC501A DETECTOR FOR MONITORING 14 MeV NEUTRONS FROM A DEUTERIUM-TRITIUM SOURCE

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Transmutation of spent nuclear fuel (SNF) is a key technology for a sustainable nuclear energy, being the ADS one of the explored concepts to reduce its radiotoxicity and volume. A key parameter in the future ADS facilities will be the monitoring of the reactivity, being the accelerator intensity, the neutron source intensity and the power the relevant parameters to be determined on-line. Nowadays, most of the experiments carried out to study the kinetic properties of ADS and to develop ADS control systems use deuterium-tritium reactions to generate intense neutron sources. The necessary experimental determination of the neutron source intensity relies in measuring neutrons with a different energy spectrum than those originated by fission within the reactor. This method will be applied in future ADS facilities for neutrons with energies > 50 MeV, and can be used in reactors driven by a deuterium-tritium source measuring neutrons with energies > 7 MeV. We have used a BC501A organic scintillator to measure high-energy neutrons coming from the GENEPI-2 (CNRS-Grenoble) neutron source. The source intensity was demonstrated to follow a linear dependence on the deuterium beam current for intensities up to ~10^{10} deuterium/pulse.

I. INTRODUCTION

Neutron detection plays a key role in many areas of interest not only in nuclear physics, but also in technological and medical applications. The Nuclear Innovation group at CIEMAT-Madrid is developing neutron detectors and neutron detector applications in several projects concerning measurements of actinides cross-sections (n_ToF, Ref. 1), nuclear structure and nuclear astrophysics (DESPEC, Ref. 2), experimental nuclear reactors (Ref. 3) or partitioning and transmutation projects (Ref. 4).

Transmutation of spent nuclear fuel (SNF) is a key technology for a sustainable nuclear energy, thus many efforts have been made worldwide in the frame of several R&D projects for its validation (Ref. 3 - Ref. 5). This technique consists on reducing the radiotoxic inventory of the high-level radioactive waste by fissioning the plutonium and minor actinides from the SNF. One of the explored concepts is developing fast neutron spectrum sub-critical reactors driven by a particle accelerator (ADS). In the final application the neutrons will be produced by protons accelerated to several hundred MeV impinging onto a spallation target of a heavy metal (Ref. 6). Nowadays, the deuterium-tritium sources are reliable intense neutron sources also driven by an accelerator, being used in present experiments to improve our understanding on the kinetical properties of the ADS and to develop ADS control systems. The MUSE experimental program performed at the fast MASURCA facility in Cadarache, has used this kind of setup to study ADS kinetics in the Fifth Framework Program of the European Union (Ref. 7). Those studies will be continued in the YALINA facility (Ref. 8 – Ref. 9) placed in Minsk. In this facility, one of the worldwide strongest deuterium-tritium source is coupled to a fast/thermal subcritical assembly. The measurements presented in this paper have been developed for the preparation of the YALINA neutron source monitoring system.

A key point of the future ADS facilities will be the on-line monitorization of the subcritical assembly reactivity (ρ). This requires the monitoring of three quantities, the accelerator intensity (I_a), the neutron source intensity (S) and the core power (neutron flux) P. In order to monitor the reactivity, actually two ratios must be determined, S/I_a and P/S. The loss of proportionality between the core power and the accelerator intensity could mean a modification of the sub-critical core or the target properties, however, the neutron source intensity is not affected (or only slightly) by the core properties. The experimental determination of the neutron source intensity relies in measuring neutrons with a different energy spectrum than those created by fission within the reactor. In the case of deuterium-tritium sources we will measure neutrons above ~ 7 MeV, while in future ADS the measured neutrons might have energies above 50 MeV.

In this work we have used a BC501A (Ref. 10) liquid organic scintillator to measure high-energy neutrons coming from a deuterium-tritium source. Organic scintillators have been widely used as neutron detectors in experimental physics because of their discrimination properties. The recoil energy deposited within the organic liquid is transformed into light, being the pulses suitable described by, at least, 2 exponential decays with very different decay times. A fast component of the order of few ns and a slow component of the order of 100 ns (Ref. 11). The relative weight of slow and fast components of the signal depends strongly on the primary ionizing particle, thus being suitable for neutron-gamma discrimination. In addition, the BC501A detector (filled with NE123 liquid) has an enhanced emission of delayed light (slow component), being specially suitable for Pulse Shape Discrimination (PSD).

II. EXPERIMENTAL SETUP

The neutrons measured in this experiment are created by 250 keV deuterons impinging onto a tritium target at the CNRS laboratory in Grenoble. They traverse the slowing-down-time spectrometer and reach the Bicron BC501A neutron detector. The slowing-down-time spectrometer is a cubic assembly of 46.5 tons of pure lead (99.99 %), consisting of eight blocks of 80x80x80 cm^3. A central channel allows the insertion of the glove finger of the accelerator whose end is the tritium target. Each block has two channels of 10x10 cm^2 of section parallel to the beam axis, which are used for block handling and detector insertion. Pure lead was chosen to ensure that impurities (mainly silver, bismuth, cadmium, copper, antimony and tellurium) are < 5 ppm.

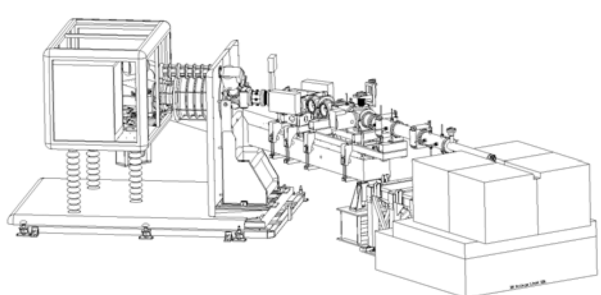

Fig. 1. Schematic view of the LPSC-GENEPI-2 accelerator coupled to the lead slowing-down-time spectrometer (the top part of the spectrometer has been removed for clarity)

The GEnerateur de NEutrons Pulse Intense 2 (GENEPI-2) consists of a duoplasmatron source producing fast deuteron pulses < 1 μs. This pulse duration corresponds to the slowing-down time necessary for a 14 MeV neutron to reach 100 keV. The repetition rate of the source can vary from a few Hz to 5 kHz. The deuterons are accelerated to the nominal energy of 250 keV, with a maximum peak intensity of 50 mA. They are then driven through the glove finger onto a titanium-deuterium or titanium-tritium target. The nuclear reactions $D(d,n)^3He$ or $T(d,n)^4He$ produce neutrons with energies close to 2.67 and 14 MeV, respectively. With a tritium target, the source can produce typically $5x10^6$ neutrons per pulse in 4π sr.

The BC501A scintillation detector manufactured by Saint Gobain, consists of a stainless steel cell of 12.7 cm length and 12.7 cm diameter, filled with the organic liquid scintillator NE213 and coupled to a Hamamatsu R877-01 photomultiplier (PM). The liquid of the detector has a portion of naphtalene ($C_{10}H_8$) and xylene (C_8H_{10}), which act as a wavelength shifter, resulting in a maximum light emission at 425 nm, corresponding to the maximum sensitivity of the PM, located at 420 nm.

The signals coming from the PM anode have been recorded with a digital oscilloscope LeCroy LC574AM of 1 GS/s and 8 bit resolution, used as flash ADC. The oscilloscope is controlled via GPIB by a PC and the signals further processed with specific software algorithms developed at CIEMAT.

III. PULSE SHAPE ANALYSIS

Digital electronics has many advantages handling with data analysis. The primary signals are recorded, being thus possible to perform the analysis offline, allowing the control of the systematic uncertainties while keeping the access to the relevant parameters of the signal (amplitudes, timing, etc). A large amount of data must be processed in a standard experiment, consequently fast and accurate algorithms must be developed in order to extract key parameters from the recorded signals.

The liquid organic scintillators have a delayed light emission depending on the primary ionizing particle. The neutrons deposit their energy in the detector mainly by proton recoil, while photons interact with the electrons in the medium, being different, in both cases, their light emissions. The protons have higher ionization density, hence favoring the excitation of molecular levels with a delayed decay compared with those levels mainly excited by photon interactions. This effect results in a larger tail in the case of signals coming from neutron interactions, as can be seen in figure 2, and can be used for neutron-gamma discrimination methods.

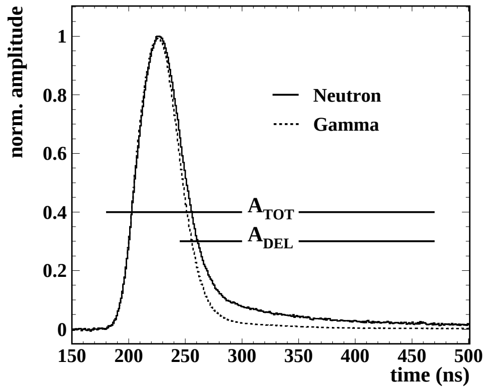

Fig. 2. Typical deposited energy in the BC501A scintillator for photons (dot line) and neutrons (solid line) coming from an Am/Be.

One standard algorithm for neutron-gamma discrimination consists in the integration of the signal areas in two different time intervals, denoted by A_{TOT} and A_{DEL} in figure 2. The discrimination is hence achieved by comparing the total area of the signal with the delayed area corresponding to the tail of the signal. This is shown in figure 3, where two clear regions appear in this scatter plot, corresponding to the neutron and photon interactions within the detector. The neutrons are clearly distinguished in this figure by means of their large delayed area. As stated in Ref. 14, this method cannot deal with very low amplitude signals and, in addition, pile-up events closer than 150 ns can not be resolved with this procedure.

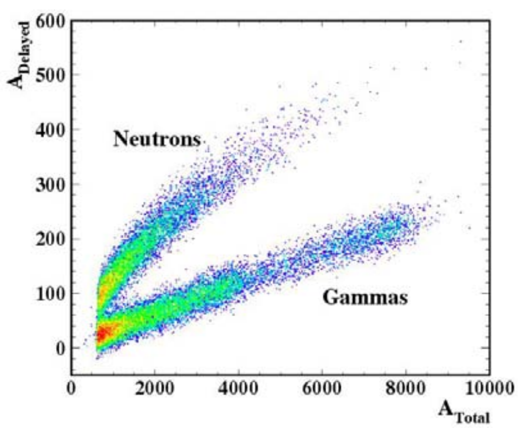

Fig. 3. Scatter plot of the total and delayed area for each measured signal coming from an Am/Be source. Both regions, corresponding to neutrons and photons are clearly distinguished.

A more powerful neutron-gamma discrimination method was developed by Guerrero et al. (Ref.14), based on a one-parameter fit to the true-shape of the detector. This method relies on the assumption that the signal shape for neutrons and gammas are intrinsically different and do not depend on the amplitude of the signal, or if it does, this dependence can be parameterized. Thus, average response signals (¨*true-shapes*¨) of the BC501A detector for neutron and gamma interactions are determined from a large number of individual pulses. The true-shapes for a given experimental conditions were shown in figure 2.

The particle discrimination is achieved by performing a least squares fit to the neutron and gamma true shapes, leaving the amplitude as the free parameter. This method involves only fast arithmetic operations and the best χ^2 provides the identification of the primary ionizing particle. Figure 4 shows an example of the fit procedure described above and, as can be observed, the measured particle corresponds to a neutron.

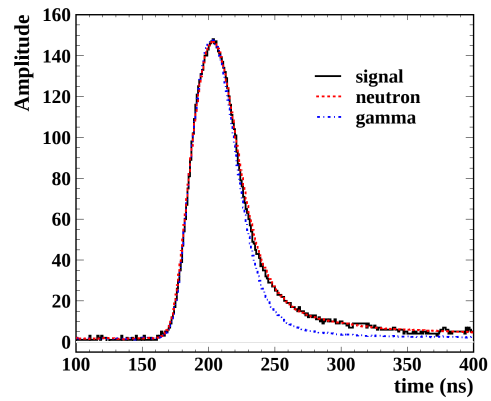

Fig. 4. Example of the fit to the true-shape method. The measured signal (solid line), neutron reference (dot line) and gamma reference signals (dot-dashed line) are shown in the figure. The best fit corresponds to a neutron particle coming from an Am/Be source.

In figure 5 we show the χ^2 distribution for a collection of 50000 signals from an Am/Be source measured in this work. As can be observed, the differences between the neutron and gamma shapes are large enough for particle discrimination.

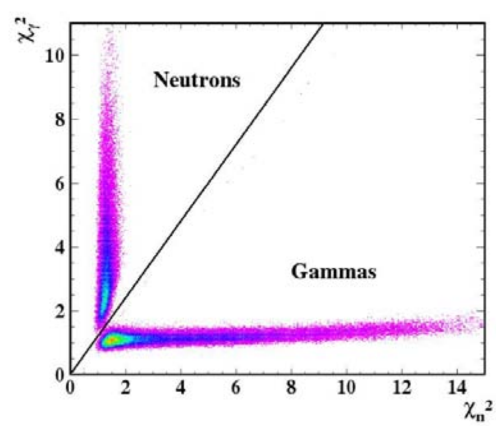

Fig. 5. χ^2 distribution of the fit to neutron and gamma shapes for 50000 signals measured with and Am/Be source.

It has been demonstrated (see Ref.14) that the neutron/gamma discrimination depends on the signal amplitude. For low amplitudes, the fit-to-shape method has been found to perform reliable particle identifications where the area method can not be used. Concerning the pile-up, the fit-to-shape method can be used to identify events in a high counting rate environment, being very suitable for experiments with high background, as a nuclear reactor. We were able to identify, with high efficiency, signals separated by 45-50 ns. In figure 6 we show an example of a pile-up reconstruction.

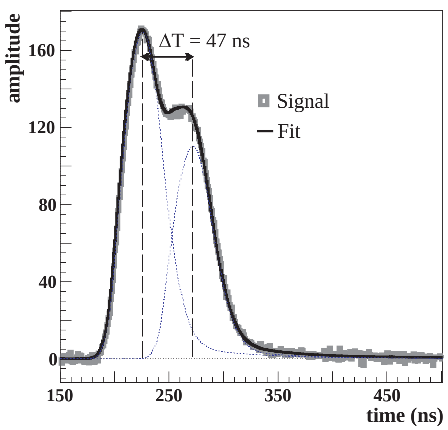

Fig. 6. Example of pile-up event reconstruction. The signals are separated by 47 ns, corresponding approximately to the lower limit of particle discrimination.

IV. RESULTS

The Pulse Shape Discrimination method described above were used to disentangle neutron and gamma particles coming from the deuterium-tritium reactions at the GENEPI-2 accelerator. In this work we have measured the neutron spectra for several intensities of the primary deuterium beam in order to explore the response of the BC501A detector under several experimental conditions. In the solid line of figure 7 we show a typical total spectrum (neutrons plus photons) measured in this work. The dashed spectrum in the figure represents the measurements at a similar beam intensity with lead collimators placed forward in the beam direction in order to study their influence in the neutron flux.

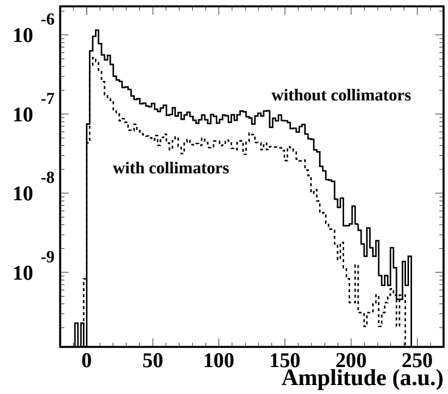

Fig. 7. Measured total spectrum for a given beam intensity (solid line) and for a similar intensity with a collimator placed in the neutron flight path (dashed line). Both spectra have been normalized to the beam current.

In order to monitor the deuteron beam current, we made use of a Faraday cup. In addition, a silicon detector was placed backward in the beam direction in order to measure the back-scattered α-particles from the fusion reaction D+T→ α + n (14 MeV). In the top panel of figure 8 we show the number of single α-particles measured by the silicon detector as a function of the deuteron beam current measured with the Faraday cup. The uncertainty in the Faraday cup was estimated in a 5 %, while only the statistical uncertainty is considered for the silicon detectors. There exists a clear proportionality between both quantities in the intensity range shown in the figure. This proportionality was determined with a χ^2 of 1.016 and 2.3 % of uncertainty in the slope of the fit. Regarding that the number of α-particles emitted by the tritium target are directly related to the number of deuterium-tritium fusion reactions, this proportionality can be used to estimate the α intensity as a direct measurement of the neutron source intensity.

However, at higher intensities, the probability of multiple α events in the silicon detector increases, leading to a loss of proportionality between the single α process and the deuteron current. The proportionality can be recovered using the 2-α, 3-α, … events as explained in Ref.15. However, in this work we will constraint the use of the experimental data to the low intensity range where the single α counting is proportional to the neutron production rate.

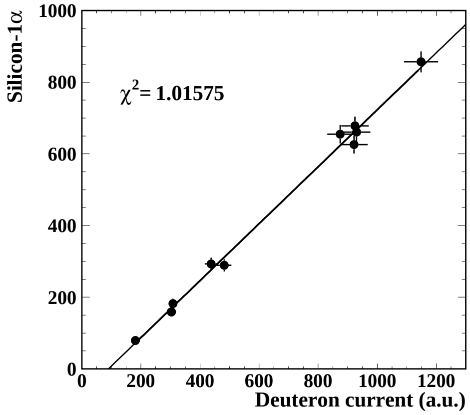

Fig. 8. (Top panel) Integrated deuteron current versus the number of 1-α events in the silicon detector. The offset in the figure corresponds to the leak current in the Faraday cup.

The main aim of this work is to check the proportionality between the neutron source intensity and the number of neutrons detected in the BC501A liquid scintillator. Nevertheless, we are interested in the high-energy region of the neutron spectrum, thus we will cut the measured spectrum and we will restrict our analysis to the most energetic neutrons. The influence of the cut was explored (see Ref. 16) and we concluded that any cut corresponding to neutron energies above ~ 4 MeV provides equivalent description of the experiment. Consequently we have selected the cut in the neutron spectra at 80 ADC channels, corresponding to neutrons with energies larger than ~ 7 MeV. In figure 9 we show the number of neutrons whose deposited energy in the BC501A detector was beyond the selected energy cut. As can be observed in the figure, the data follow a linear dependence with the deuteron beam current. This dependence can be determined with a χ^2 of 1.022 and a uncertainty in the fit slope of 2.28%. In the figure we also show the residues of the fit, where only two experimental data are beyond one σ from the best fit.

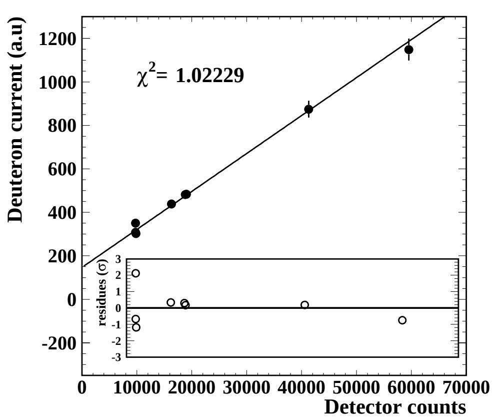

Fig. 9. Number of neutrons detected in the BC501A for amplitudes larger than 7 MeV as a function of the deuteron beam current. The residues corresponding to the best fit of the data are also shown in the figure.

In the figure 10, we show the same data of figure 9 as a function of the 1-α signal from the silicon detectors, which provides an indirect measurement of the neutron source intensity. The measured data also follow a linear behavior with a χ^2 of 1.067. Based on these results, we can state that the number of detected neutrons depends, in a proportional way, to the Deuterium-Tritium neutron source intensity and we can determine this source intensity with a precision of 2.05 %, estimated from the uncertainty in the slope of the linear fit. This precision might be improved by measuring the experimental points with more statistics in the 1-α number of counts.

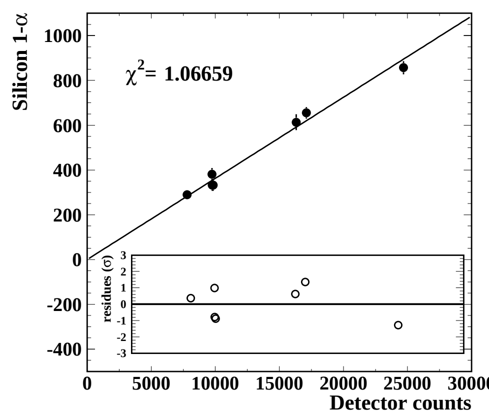

Fig. 10. Number of neutrons detected in the BC501A for amplitudes larger than 7 MeV as a function of the 1-α events in the silicon detector. The residues corresponding to the best fit of the data are also shown in the figure.

V. CONCLUSIONS

A BC501A neutron detector was used in order to explore the proportionality between the beam current and the measured neutron spectra in a 14 MeV Deuterium-Tritium neutron source. Neutron-gamma discrimination was achieved by means of the fit-to-shape method, based on the different delayed signals of the BC501A depending on the primary ionizing particle. The number of detected neutrons with deposited energies beyond ~ 7 MeV was demonstrated to follow a linear dependence with the deuteron beam current up to ~10^{10} deuterium/pulse, this linearity was determined with a precision of 2.28 %. The number of detected neutrons was also demonstrated to be linear on the intensity of the Deuterium-Tritium source by means of the silicon detector for the 1-α signals. This linearity was determined with a precision of 2.05% up to deuterium beam current of ~10^{10} deuterium/pulse in the case of the 1-α process.

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