Developments in neutron metrology at the Institute for Radiological Protection and Nuclear Safety in 2013 and 2014

1 Introduction

LNE-IRSN is LNE (Laboratoire National de métrologie et d’Essais) designated institute (DI) in charge of the neutron fluence and dose equivalent quantities. IRSN laboratory for neutron metrology and dosimetry (LMDN) disposes of several facilities producing reference neutron fields and performs neutron spectrometry with several types of instruments in order to determine these quantities with the best achievable accuracy.

2 Neutron reference fields

2.1 Radionuclide sources

The neutron irradiator facility consists in radionuclides sources of $^{241}$Am-Be and $^{252}$Cf (moderated or not with a heavy water sphere). Up to now, it is the only facility where IRSN proposed CMCs is the irradiator with radioactive sources $^{241}$Am-Be and $^{252}$Cf (moderated or not with heavy water sphere).

The $^{241}$AmBe source being 25 years old, will be replaced in 2015 with a new source (592 GBq). This source will be calibrated at both NPL and LNE-LNHB manganese baths allowing a comparison between the calibration performed in these two NMIs. The $^{252}$Cf neutron source being 10 years old, the correction for $^{250}$Cf contribution can not be neglected. A fluence cross-calibration of a Berthold survey meter is therefore performed with NPL $^{252}$Cf in order to ensure the reference values at LNE-IRSN field. This $^{252}$Cf source is foreseen to be replaced by a new one in 2016.

2.2 AMANDE : Mono-energetic neutron fields

AMANDE produces mono-energetic neutron fields within the energy range from a few keV up to 20 MeV. Neutrons are created using nuclear reactions between accelerated protons, deuterons and thin targets like scandium, lithium, deuterium, tritium, as defined by ISO 8529-1 standard. The AMANDE facility is based on a 2 MV HVEE Tandetron accelerator, which has been installed at the end of 2004 in a low scatter building.

Related metrological activities in 2013 and 2014 concern:
- evaluation of CCRI-K11 comparison, measurements having been performed in 2011 and 2012.
- the further development of two nucleus recoil telescopes for both energy and fluence reference determination.
- several studies for reference traceability and uncertainty budgets in order to establish a quality control following the ISO-17025 standard (accreditation in 2016)
- calibration of a Bonner sphere system based on central counter filled with low pressure $^3$He mixed with $^4$He.

Due to a huge upgrade of the facility to develop and host a second beamline dedicated to cell irradiation with a microbeam, for radiobiology research studies, AMANDE facility is shutted down since March 2014 and will restart during 2016.

2.2.1 CCRI-K11 comparison

From September 2011 to October 2012, the eleventh key comparison, named CCRI(III)-K11, took place at the AMANDE facility of the LNE-IRSN, in France. Participants from nine NMIs (NPL, VNIIM, CIAE, IRMM, PTB, NIST, AIST, LNMRI and IRSN) came with their own primary reference instruments, or instruments traceable to primary standards, with the aim of determining the neutron fluence per monitor count at four monoenergetic neutron fields: 27 keV, 565 keV, 2.5 MeV and 17 MeV. Stable monitoring and control measurements demonstrated the reproducibility and the stability of the neutron fields over the duration of the comparison of more than one year, even with a change of target thickness at 17 MeV.

LNE-IRSN, as pilot laboratory, provided the spectral fluence including the uncollided, and therefore almost monoenergetic, neutrons and the neutrons scattered in the target assembly. The monitor data recorded during the measurement campaigns in which the laboratories participated, corrected for background and dead time, were also provided. Seven participants (CIAE and LNMRI could unfortunately not deliver results in due time) determined the fluence in vacuum at a common point of measurement, at 0 degrees and a distance of one metre, related this fluence to the properly corrected reading of a selected neutron monitor and evaluated a detailed uncertainty budget.

The reported data were then evaluated. The weighted means of all data obtained for one neutron energy served as the key comparison reference value and results are shown in the figure 1. Details on the CCRI(III)-K11 comparison is given in [1].

Main conclusions of this comparison are:
- key comparison reference value (KCRV) : the consistency of the results was verified with a $\chi^2$ test, following the method described in reference [2]. Since this test was successful at all energies, the weighted mean of all participants values at a given energy was considered as the KCRV;
- the VNIIM values are, however, systematically lower than the KCRV suggesting that the calibration of the VNIIM instrument needs to be checked;
- a deviation between the values obtained by long counters and other instruments (Recoil proton telescopes, fission chamber or activation foil) is observed at 17 MeV. There could therefore be a device dependent bias that needs more investigation to be confirmed.
2.2.2 Nucleus recoil telescope

LNE-IRSN is developing two different but complementary Recoil Proton Telescopes (RPT) in collaboration with CNRS (French National Center for Scientific Research). The main purpose of these two telescopes is to characterize, in terms of both energy and fluence, the IRSN mono-energetic neutron fields at AMANDE facility.

The first RPT, called ATHENA (Accurate Telescope for High Energy Neutron metrology Applications), has been developed in collaboration with CNRS/IPHC (‘Institut Pluridisciplinaire Hubert Curien’ - Strasbourg). This RPT is based on layers of active pixel CMOS sensors. The project already gave birth to a first prototype that can cover an energy range from 5 MeV to 20 MeV and measure neutron fluence rate up to $10^6$ cm$^{-2}$.s$^{-1}$. The neutron energy resolution was experimentally determined between 5 and 10% depending on the radiator’s thickness. The neutron fluence measured by ATHENA at 14 MeV and 17 MeV has been compared with reference values determined respectively with IRSN long counter PLC and liquid scintillator BC501A leading to a good agreement as relative deviations are respectively of (5±5)% and (7±6)%.
A second and final prototype is already under development. The main focus is to be able to support higher neutron fluence rates. In that aim, IPHC designed a new CMOS sensor 400 times faster than the old one allowing, in theory, measurements in fluence rates up to $10^8 \text{ cm}^{-2} \cdot \text{s}^{-1}$. This upgrade has also required a redesign of the telescope's geometry. The final prototype is expected to be fully operational at the end of 2015. The possibility to extend the energy range of this new design up to several hundreds of MeVs is currently investigated.

The second RPT is a gaseous $\mu$-time projection chamber (µ-TPC) with spectrometry capabilities in the neutron energy range between 8 keV and 5 MeV. This project is developed within the framework of a collaboration with CNRS-MIMAC unit (Directional non baryonic dark matter search field). Since 2013, neutron energy measurements were performed at monoenergetic neutron fields of 8 keV, 27 keV, 127 keV, 144 keV, 250 keV and 565 keV, produced by AMANDE facility, as well as at the $^{252}$Cf neutron field of IRSN CEZANE facility. A high rejection power of the detector has been observed between photons and recoil nuclei, thanks to coincidences between different sensitive parts of the detector. Additionally, these measurements allowed the study of a new reconstruction algorithm to improve the low energy protons treatment. Neutron energies were quite well reconstructed compared to TARGET and MCNPX simulations even if a slight bias is observed. This bias is coming from the energy dependence of the W value, the energy required to produce an ion pair (ICRU 31). In the figure 3, the neutron energy distribution is shown for the 27 keV measurements and a complete simulation of the detector response.
Figure 3: Neutron energy determination at 27 keV with $\mu$-TPC. The black curve is the neutron energy distribution measured by the $\mu$-TPC at the AMANDE facility. The red curve is the calculated fluence energy distribution folded with the simulated detector response and normalized to the neutron fluence determined by the IRSN PLC.

To remove the energy bias, a specifically dedicated ion source named COMIMAC, shown in the figure 4, has been set up at AMANDE facility. This ion source, developed by CNRS, is able to produce proton and electron beams in the 1 to 50 keV energy range and will allow the energy calibration of the detector with electrons as well as the experimental determination of the gases ionisation quenching factors (IQF), related to the W value.

To reduce the neutron scattering in the walls of the detector, a new chamber, shown in the figure 5, was made based on MCNPX simulations and mechanics studies. The proportion of scattered neutrons inside the chamber was reduced by more than a factor 10, and the weight of the detector was noticeably reduced.

A gas control system dedicated to the $\mu$-TPC was designed, tested and used during the neutron energy measurements. This system enables the circulation of a mix of gas knowing precisely the pressure and the proportion of each gas. A gas flow with a closed loop is being developed to ensure the measurement repeatability.
This work has demonstrated the µTPC measurement capabilities. To consider this detector as a standard spectrometer, the measurement procedures and conditions will be optimised thanks to this work. Measurements at several reference neutron fields will be performed. Additionally, the µTPC measurement uncertainties will be reduced by IQF measurements and gas composition determination.

2.2.3 Calibration of the HERMEIS system for secondary neutrons at proton/hadron therapy facilities

HERMEIS-m (High Energy Range Multisphere Extended IRSN System for medical applications) is a Bonner spheres neutron spectrometer equipped with 14 moderator spheres and a low pressure $^3$He gas filled detector. This version of the spectrometer$^1$ was designed and developed to perform measurements mainly at hadron therapy facilities. The proportional counter is manufactured by LND, Inc. and it is nominally filled with 1 Torr $^3$He, 760 Torr $^4$He and 22.83 Torr of CO$_2$.

During data acquisition, the pulse height spectrum (PHS), shown on Figure 6, from the analogic signal is not similar to that of the well know distribution from the $^3$He(n,p)T reaction.

$^1$ Another version of HERMEIS is equipped with a high pressure $^3$He proportional counter; it is dedicated to measurements of low neutron fluence rates; it was especially developed for the neutrons from the cosmic radiations, as each of the 14 spheres can be equipped with a $^3$He counter and they can thus be run in parallel.
One of the hypotheses to explain the shape of the PHS was to consider the neutron reactions with $^4\text{He}$ (and CO$_2$ in some extent). To characterize this HERMEIS-m system, some measurements were performed with monoenergetic neutrons, of 144 keV, 565 keV, 1.2 MeV and 2.5 MeV, at the AMANDE facilities. These energies were chosen in order to check the behaviour of the response in a region where the $^4\text{He}$ neutron cross-section exhibits a broad peak, as shown on Figure 7. The preliminary response functions from Monte-Carlo simulations, where the $^3\text{He}$ and $^4\text{He}$ had been considered, are shown in Figure 8. The behaviour in the region around 1 MeV is clearly due to the $^4\text{He}$ cross-section (elastic scattering).

![Cross section vs Energy graph](image1)

**Figure 7**: Total neutron cross-sections for $^3\text{He}$ and $^4\text{He}$ from ENDF/B-VII.1 (JANIS 4.0)

![Response vs Neutron energy graph](image2)

**Figure 8**: Preliminary response functions from MCNPX calculations, considering neutron reactions with $^3\text{He}$ and $^4\text{He}$ gases inside the proportional counter.
The preliminary experimental responses are compared to the (preliminary) calculated values, in Figure 9. The shape of the response functions are comparable, which confirms that neutron reactions the $^4$He has to be considered, but for all the 6 spheres, the experimental values are systematically below the calculated ones. Further MCNPX Monte-Carlo simulations are being undergone considering neutron reactions with all gases and variations of the gases pressure.

Figure 9: Comparison of the experimental and calculated responses of HERMEIS-m, for the neutron energies of 144 keV, 565 keV, 1.2 MeV and 2.5 MeV (preliminary results).
Publication list related to neutron metrology of LNE-IRSN (2013-2014)


