Thermal neutrons registration by xenon gamma-ray detector

A E Shustov, I V Chernysheva, V V Dmitrenko, A G Dukhvalov, K V Krivova, A S Novikov, D V Petrenko, K F Vlasik, S E Ulin and Z M Uteshev
National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe highway 31, Moscow, 115409, Russia
E-mail: AEShustov@mephi.ru

Abstract. Experimental results of thermal neutrons detection by high pressure xenon gamma-ray spectrometers are presented. The study was performed with two devices with sensitive volumes of 0.2 and 2 litters filled with compressed mixture of xenon and hydrogen without neutron-capture additives. Spectra from Pu-Be neutron source were acquired using both detectors. Count rates of the most intensive prompt neutron-capture gamma-ray lines of xenon isotopes were calculated in order to estimate thermal neutrons efficiency registration for each spectrometer.

1. Introduction
There is a wide range of neutron detectors based on different materials: scintillators, semiconductors, gas mixtures with high neutron capture cross-section additive ($^3$He, $^{10}$BF$_3$, $^6$Li) and so on. Some of materials are able to simultaneously register neutron and gamma-rays, e.g. $^4$LiI(Eu). In our previous paper [1] we showed that the high pressure xenon gamma-ray spectrometer (HPXe) can be used for thermal neutron detection. Natural xenon is a mixture of isotopes with neutron capture cross-section acceptable for neutron detection by means of prompt gamma-ray registration. In this research we have improved our analyzing technique for neutron efficiency calculation and test using HPXe with sensitive volumes of 0.2 and 2.0 litters.

2. Xenon gamma-ray spectrometers
The xenon spectrometer is a gamma-ray detector based on cylindrical ionization chamber [2] operating in pulse mode. It is filled with high pressure (40 atm.) xenon and hydrogen mixture and has the Frisch grid. Main parameters of HPXe 2.0L and 0.2L are shown in table 1.

| Detector   | Energy resolution at 662 keV (%) | Xenon mixture density (g·cm$^{-3}$) | Cathode diameter (cm) | Grid diameter (cm) | Anode diameter (cm) | Gamma-rays energy range (MeV) |
|------------|----------------------------------|-------------------------------------|------------------------|-------------------|---------------------|-------------------------------|
| HPXe 0.2L  | 2.4                              | 0.4                                 | 3.8                    | 1.2               | 0.4                 | 0.03–2                        |
| HPXe 2.0L  | 2.0                              | 0.3                                 | 11.3                   | 4                 | 2                   | 0.05–3                        |

HPXe 2.0L has high energy resolution 2.0% for 662 keV that is better than commonly used scintillator detectors based on NaI or CsI crystals.

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd
3. Geometry of experiments
Detectors were exposed to thermal neutrons flux. Neutrons emitted by Pu-Be source were moderated using polyethylene container with 11 cm thick wall. The geometry scheme of the experiment is shown in figure 1.

![Scheme of experiment](image)

**Figure 1.** Scheme of experiment.

To suppress gamma-rays emitted during neutrons capture reactions inside polyethylene container, 3.5 cm thick lead was used. Pu-Be source has $4.6 \times 10^6$ Bq activity. Detector was placed at 4 cm from Pb shield and 33.5 cm from neutron source. Measurements by $^6$LiI(Eu) detector placed at the same point gave value of flux $27$ neutrons·sec$^{-1}$·cm$^{-2}$.

4. Gamma-ray spectra from Pu-Be source
Before the experiment a gamma-ray background in laboratory without neutron source for both detectors was measured. After that measurements of Pu-Be neutron source surrounded by moderator and Pb shield were done. The results are shown in figures 2 and 3.

![Spectra](image)

**Figure 2.** Experimental spectra of neutron source and background measured by HPXe 2.0L detector.

**Figure 3.** Experimental spectra of neutron source and background measured by HPXe 0.2L detector.

Spectra with subtracted background for each detector at most interesting region are shown in figures 4 and 5.
Detailed analysis of gamma-ray lines and results are discussed in next section.

5. Thermal neutrons detection by the xenon spectrometer

Natural mixture of xenon consists of nine isotopes. Some of them have high thermal neutron capture cross-section. Abundance and neutron capture cross-section for xenon isotope are presented in table 2.

| Isotope | 124 Xe | 126 Xe | 128 Xe | 129 Xe | 130 Xe | 131 Xe | 132 Xe | 134 Xe | 136 Xe |
|---------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Abundance, ε (%) | 0.09 | 0.09 | 1.92 | 26.44 | 4.08 | 21.18 | 26.89 | 10.44 | 8.87 |
| Thermal neutron capture cross-section, σ₀ (barn) | 165 | 3.8 | 5.2 | 21 | 4.8 | 85 | 0.45 | 0.27 | 0.26 |
| Effective cross-section, σ₀·ε (barn) | 0.15 | 0.003 | 0.1 | 5.55 | 1.96 | 18.0 | 0.12 | 0.028 | 0.023 |

After capture reaction nuclei usually emit gamma-ray. In our previous research [1] we used the most intensive 668 keV gamma-ray line for neutron detection. This line is a result of neutron radiative capture reaction with $^{131}$Xe. Other isotopes also emit gamma-rays due to interaction with neutrons. So these gamma lines seen in spectrum can be used for neutron detection. Multiline detection approach is a more reliable method that allows us to avoid errors and gives more evidence of neutron flux detection. Detailed information about prompt gamma-rays from Xe isotopes is shown in table 3.

| Energy (keV) | 483.7 | 536.2 | 586.2 | 600.2 | 630.3 | 667.8 | 772.7 | 1317.9 | 1985.7 | 6467.1 |
|-------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Isotope     | $^{131}$Xe | $^{129}$Xe | $^{129}$Xe | $^{131}$Xe | $^{131}$Xe | $^{131}$Xe | $^{131}$Xe | $^{131}$Xe | $^{131}$Xe | $^{131}$Xe |
| $\sigma_{\gamma}(E_{\gamma})$ (barn) | 0.55 | 1.71 | 0.48 | 0.52 | 1.41 | 6.7 | 1.78 | 0.89 | 0.54 | 1.33 |
| Related intensity (%) | 8.21 | 25.52 | 7.16 | 7.76 | 21.05 | 100 | 26.57 | 13.28 | 8.06 | 19.85 |

In this research we used 668, 630, 536 and 773 keV gamma-ray lines for calculation neutron efficiency detections that have high partial elemental gamma-ray cross-sections $\sigma_{\gamma}(E_{\gamma})$ [3]. $\sigma_{\gamma}(E_{\gamma})$ is defined by product $\epsilon \cdot P(E_{\gamma}) \cdot \sigma_{0}$, where $P(E_{\gamma})$ is the absolute probability of gamma emission. By area calculation under the peaks we can estimate efficiency using information from $^6$Li(Eu) measurements.
$^{6}$Li(Eu) detector placed at same point gave the value of flux $27\ \text{neutrons}\cdot\text{sec}^{-1}\cdot\text{cm}^{-2}$. Final values are shown in tables 4 and 5.

**Table 4.** Count rate under the peaks and efficiency registration for HPXe 0.2L detector.

| Energy (keV) | Count rate (cps) | Efficiency registration (%) |
|-------------|------------------|-----------------------------|
| 536.2       | 0.137±0.016      | 0.027±0.003                 |
| 630.3       | 0.091±0.015      | 0.018±0.003                 |
| 667.8       | 0.404±0.014      | 0.079±0.003                 |
| 772.7       | 0.078±0.012      | 0.015±0.002                 |

**Table 5.** Count rate under the peaks and efficiency registration for HPXe 2.0L detector.

| Energy (keV) | Count rate (cps) | Efficiency registration (%) |
|-------------|------------------|-----------------------------|
| 536.2       | 2.7±0.2          | 0.058±0.004                 |
| 630.3       | 2.0±0.3          | 0.042±0.005                 |
| 667.8       | 9.3±0.2          | 0.199±0.005                 |
| 772.7       | 1.41±0.13        | 0.030±0.003                 |

Total efficiency registration of thermal neutrons by 0.2 litters xenon gamma-ray detector is $(0.138\pm0.006)\%$. In paper [1] efficiency of 0.2L detector estimated using only 668 keV gamma-ray line was $(0.079\pm0.003)\%$. Total efficiency registration of thermal neutrons by 2.0L xenon gamma-ray detector is $(0.329\pm0.009)\%$.

**6. Conclusion**
The results of thermal neutrons registration by the high pressure xenon detector showed that spectra contain prompt gamma-ray lines from radiative neutron capture reactions of xenon isotopes. Spectrometers can be used as a neutron detector with an efficiency $(0.138\pm0.006)\%$ and $(0.329\pm0.009)\%$ for detectors with volume 0.2 and 2.0 litters, respectively. Improved analyzing technique based on multiline detection allows to increase efficiency of HPXe 0.2L detector from 0.078 to 0.138%.

**Acknowledgments**
Authors wish to acknowledge the Center of fundamental researches and particle physics. This work was partially supported by MEPhI Academic Excellence Project (contract No. 02.a03.21.0005, 27.08.2013).

**References**
[1] Dmitrenko D et al. 2012 Detection of neutrons and gamma-rays by a xenon pulsed ionization chamber *Instrum. Exp. Tech.* **55** 419
[2] Novikov A et al. 2014 Xenon detector with high energy resolution for gamma-ray line emission *Proc. SPIE* **9213** 921318
[3] International Atomic Energy Agency 2007 *Database of Prompt Gamma Rays from Slow Neutron Capture for Elemental Analysis* (Vienna) p 124