Apparatus complex based on liquid xenon detector for gamma spectrometry in the intervals between pulses of intense radiation

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Abstract. To investigate the effects of intense radiation on the operation of the liquid xenon spectrometer we have created apparatus complex on the basis of the liquid xenon detector. The experimental setup consists of a multifunctional chamber, gas system, cooling system, temperature control system, X-ray generator, a special preamp, passive protection, scintillation monitor of the accelerator beam, thermoluminescent dosimeters, copper monitor bremsstrahlung, Ge(Li) detector. Multifunctional chamber includes a detecting unit (flat or cylindrical ionization chamber), the cleaning unit of the xenon, control unit of the purity of liquid xenon. The liquid xenon detector was irradiated by bremsstrahlung pulses of the microtron. The frequency of irradiation pulses was 400 Hz. The absorbed dose was varied from \(10^{-7}\) to 0.1 Gy per pulse. The electronic and ionic processes in liquid xenon at different radiation doses were investigated. The recovery time of the spectrometric mode of operation of the liquid xenon detector after intense pulse irradiation has been studied. Stable operation of the liquid xenon spectrometer in the intervals between the pulses of the accelerator shown for a long time.

1. Introduction

In applied and fundamental research are used intense sources of pulsed radiation: particle accelerators, neutron generators, synchrotron radiation, X-ray and gamma-ray generators. The implementation of activation analysis for the short-lived nuclides \(T_{1/2} < 1\) s is an urgent task at present time. In such studies, the detector should be located near the beam of intense radiation. The detector must detect the particles in the intervals between the pulses of the accelerator. To solve such problems require detectors that can quickly restore their spectrometric properties after each pulse of intense radiation. The noble gas detectors have a high radiation resistance, and they are the most promising detectors for such tasks [1]. Using apparatus complex on the basis of the liquid xenon detector, we investigated the electronic and ionic processes in liquid xenon under intense irradiation and spectrometric characteristics of the detector when operating in intervals between pulses of radiation. We performed the experiment on registration of short-lived isomer \(^{207m}\)Pb. To obtain experimental information on the effects of high-intensity pulsed radiation on the characteristics of the liquid xenon spectrometer such detector was located in the beam of bremsstrahlung of electron accelerator.

2. Experimental setup

The experimental setup consists of a multifunctional chamber, gas system, cooling system, temperature control system, X-ray generator, a special preamp, passive protection, scintillation
monitor of the accelerator beam, thermoluminescent dosimeters, copper monitor bremsstrahlung, Ge(Li) detector.

Multifunctional chamber is placed inside the cryostat [2]. The temperature in the cryostat was maintained via blowing of nitrogen vapors through it and stabilized at an accuracy of 1 K. Five thermocouple (copper-constantan) sensors controlled the temperature in different parts of the multifunctional chamber. During the measurements, the chamber temperature could be varied within the range 165–250 K.

The scheme of the multifunctional chamber is shown in figure 1. The multifunctional chamber includes the detection unit (3) (flat or cylindrical ionization chamber), the xenon cleaning unit (1) and the control unit of xenon purity (2). The detection unit consists of two interchangeable detectors: research flat chamber and spectrometric cylindrical chamber. Parameters of flat chamber: diameter of the electrodes is 1.8 cm, the distance between electrodes is 0.53 cm, the sensitive volume is 1.35 cm³. Parameters of cylindrical chamber: the cathode radius is 0.52 cm, the anode radius is 0.01 cm, the height is 2.8 cm, the sensitive volume is 2.4 cm³.

Figure 1. The scheme of the multifunctional chamber: 1- xenon purification unit, 2 - unit for xenon purity testing, 3 - research ionization chamber, 4 - bremsstrahlung beam from the microtron, 5 - X-rays.

Figure 2. The scheme of the apparatus for the first series of measurements: 1 - liquid xenon multifunctional chamber, 2 - Pb shield, 3 - Al absorber, 4 - W target, 5 - electron accelerator, 6 - scintillation detector.

The xenon was purified via the electric-spark method [3] in the cleaning unit. The purity of liquid xenon was determined according to capture of electrons produced by X-ray pulses in the unit for testing the xenon purity. The X-ray tube BSV-7 was located under the multifunctional chamber. The average displacement of electrons before capture were several centimeters.

Our setup was installed in the bremsstrahlung beam from the MT-25 microtron of the Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research [4]. The parameters of the microtron: the energy of the electrons in the beam of 10-25 MeV, average beam current of up to 15 µA, the pulse repetition rate of 400 Hz, pulse duration of 2.5 µs. The electron beam bombards the tungsten target (2 mm thick) with aluminum absorber (3.5 cm thick), producing bremsstrahlung with the corresponding spectrum and angular distribution.

Scintillation detector (plastic scintillator thickness of 0.5 mm and PMT-85) registered the shape of the bremsstrahlung pulses and formed the start signal. The radiation pulses have the shape of a trapezium with a duration at half maximum 2.5 µs [2]. The dose per pulse was measured by means of thermoluminescent dosimeters (aluminophosphate glass) in a series of special calibration sessions. The thermoluminescent dosimeters placed at the location of the chamber in the cryostat. The diameter and
thickness of the pellets of thermoluminescent dosimeters are 8 and 1 mm, respectively. Correction of readings of thermoluminescent dosimeters was performed on the signals in xenon at a low dose.

3. Electron and ion signals of the liquid xenon detector under intense pulsed irradiation

The flat ionization chamber was located in the detection unit of the multifunction chamber in the study of processes in the liquid xenon under intense pulse irradiation. The multifunctional chamber was located in the direct beam of bremsstrahlung radiation of microtron MT-25 (figure 2). The distance from the tungsten target to the center of the chamber was equal to 30 cm. Lead shield of variable thickness located between the tungsten target and the chamber. Figure 3 shows the dependence of the pulse dose on the thickness of lead shield for the direct beam of the microtron MT-25.

The electron current pulses of the flat chamber were recorded at a load resistance of 50 Ω ($RC \approx 10^{-7}$ s). We investigated the current pulses at the output of the xenon detector, depending on the absorbed dose per pulse. The dose range can be divided into two parts: small dose (< 0.1 mGy/pulse) and high dose (>0.1 mGy/pulse). Rise time current pulse at low doses is approximately equal to the pulse duration of radiation. At high doses, the current reaches the maximum value before the end of the pulse irradiation. At high doses, space charge formed in the detector. Space charge affects the shape of the current pulses. Figure 4 shows the dependence of the rise time of current on the dose. As is seen in figure 4, the space charge affects on the shape of the electron current at doses above 0.2 mGy per pulse.

![Figure 3. The dependence of the pulse dose on the thickness of the Pb shield.](image1)

![Figure 4. The dependence of current pulse rise time on the dose in the pulse.](image2)

The ion current pulses of the flat chamber were recorded at a load resistance of 100 kΩ ($RC \approx 10^{-4}$ s). From the experimental data we determined the mobility of positive ions in liquid xenon $\mu = (4.57 \pm 0.11) \times 10^{-3}$ sm²/(V·s) at a temperature of 230 K [4]. The obtained value of the ion mobility is in good agreement with the data of [5]. This fact means that the electric-spark method [3] cleans xenon from the electronegative impurities and the molecules that are able to intercept the charge from positive ions.

A space charge is produced in the chamber under high intensity irradiation. The critical dose $D_{cr}$ takes into account the influence of the space charge [2]. For the flat chamber $D_{cr} = 19$ μGy at the potential difference between the electrodes 5 kV. When the dose is less than the critical the electrons leave the volume of the chamber within a few microseconds. When the irradiation dose above critical, the loss of electrons occurs due to the recombination. This process can last hundreds of microseconds.
After the restoration of the electric field the electrons in a few microseconds leaving the chamber. Accumulation of electrons in the chamber does not occur.  

Because the ions have a low mobility, they accumulate in the chamber even at low intensity of pulse irradiation. Therefore, the registration of gamma rays in the interval between pulses of the accelerator occurs on the ion current. In this case, the following factors [4] give the deterioration of the energy resolution of gamma spectrometer: 1) fluctuations in the ion current; 2) a change in the ion current over time between pulses of radiation; 3) the presence of the internal field of the space charge of positive ions.

4. The spectrometric characteristics of the detector during operation in intervals between pulses of radiation

The cylindrical ionization chamber [6] was located in the detection unit of the multifunction chamber in the study of spectrometric characteristics of the detector during operation in intervals between pulses of radiation. The multifunctional chamber was located at a right angle to the tungsten targets of the microtron MT-25 (figure 5). The passive protection of the chamber was located between the brake target and the chamber. In the forward direction, the thickness of shield was equal to 20 cm lead and 8 cm borated polyethylene, in all other directions - 5 cm lead and 2 cm borated polyethylene.

In the cylindrical chamber from each pulse of the accelerator is absorbed the energy of the bremsstrahlung, which in $10^4$ - $10^5$ times higher than the characteristic energy of gamma rays. This leads to large overload charge-sensitive preamplifier for each accelerator pulse. The special preamplifier has been developed, which were neutralized current pulses from the ionization chamber at the moments of accelerator pulse. The input of the main amplifier was closed at the time of transients in the preamplifier. The blocking time of the amplifier was 500 µs from the beginning of each pulse of the accelerator.

The gamma-ray source $^{137}$Cs was used to study the ability of the detector to operate in the spectrometric mode in the intervals between the pulses of intense radiation. The cylindrical chamber recorded the $^{137}$Cs spectra in the intervals between pulses the accelerator [7]. When the accelerator is off the energy resolution of the detector was 9.5%. When the accelerator is running resolution of the detector was 14%. Our experiments have demonstrated the ability of xenon detector to operate in the spectrometric mode in the intervals between pulses of intense radiation.

![Figure 5. The scheme of the apparatus for the second series of measurements: 1 - liquid xenon multifunctional chamber, 2 - polyethylene with boron, 3 - Pb shield, 4 - sample, 5 - Cu monitor, 6 - Al absorber, 7 - W target, 8 - electron accelerator.](image-url)

![Figure 6. The dependence of the isomer $^{207}$Pb yield on the maximum of bremsstrahlung energy.](image-url)
The cylindrical ionization chamber was used to study short-lived isomer $^{207m}\text{Pb}$ ($T_{1/2} = 0.8$ s). The experimental scheme is shown in figure 5. The isomer $^{207m}\text{Pb}$ formed in the reaction $^{208}\text{Pb}(\gamma,\text{n})^{207m}\text{Pb}$ under the action of gamma-rays of bremsstrahlung of the microtron [8]. To calculate the yield of isomer $^{207m}\text{Pb}$ in standard units, we used a copper monitor of bremsstrahlung. Thin Cu plate was placed in front of Pb sample. The bremsstrahlung initiated reaction $^{65}\text{Cu}(\gamma,\text{n})^{64}\text{Cu}$. The induced activity of the copper plate was measured by Ge(Li) detector. Gamma-rays (0.57 MeV and 1.06 MeV) of isomer $^{207m}\text{Pb}$ were detected by xenon detector in the intervals between the pulses of the accelerator. In this experiment, we measured the yield of $^{207m}\text{Pb}$ isomer for different beam energy of the accelerator.

5. Conclusion
Designed apparatus complex allowed to investigate the operation of liquid xenon spectrometer under conditions of intense pulsed irradiation. We investigated the electronic and ionic processes in liquid xenon under intense radiation. The recovery time of the spectrometric mode of operation the xenon detector after intense pulse irradiation was studied. We measured the mobility of positive ions in the liquid xenon. The special preamplifier allows to perform spectrometric measurements near the pulsed beam of the accelerator. The ability of xenon detector to operate in a spectrometric mode in the intervals between the pulses of intense radiation was demonstrated. We measured the yield of $^{207m}\text{Pb}$ isomer for different beam energy of the accelerator.

Acknowledgments
The author is grateful to I.M. Obodovskiy for supporting, Y.P. Gangrski and A.G. Belov for the possibility of operating on the microtron MT-25, V.G. Subbotin and S.N. Iliev for the development of a special preamplifier, V.E. Zhuchko for the possibility of using of Ge(Li) detector.

The author is grateful for the support from the National Research Nuclear University MEPhI (Moscow Engineering Physics Institute) in the framework of the Russian Academic Excellence Project (contract No. 02.a03.21.0005, 27.08.2013).

References
[1] Kirsanov M A et al. 1991 (in Russian) *Atomic Energy* 70 131 (Original Russian title: *Atomnaya Energiyu*)
[2] Kirsanov M A and Obodovskiy I M 2008 *Instr. Exp. Techn.* 51 358
[3] Pokachalov S G et al. 1993 *Nucl. Instrum. Meth.* A 327 159
[4] Kirsanov M A and Obodovskiy I M 2010 *Instr. Exp. Techn.* 53 185
[5] Hilt O and Schmidt W 1994 *J. Phys. Condens. Matter* 6 L735
[6] Kirsanov M A et al. 1991 (in Russian) *Instruments and Experimental Techniques* 1 75 (Original Russian title: *Pribory i Tekhnika Eksperimenta*)
[7] Kirsanov M A 2016 *Journal of Physics: Conference Series* 675 042014
[8] Kirsanov M A, Obodovski I M and Gangrski Yu P 1993 *Nucl. Instrum. Meth.* A 327 48