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PORTABLE NEUTRON GENERATOR WITH 9-SECTION SILICON α-DETECTOR

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Портативный нейтронный генератор с 9-секционным кремниевым α-детектором

Описаны характеристики портативного нейтронного генератора со встроенным многосекционным α-детектором для создания пучков меченых нейтронов.

Одной из отличительных особенностей такого типа генераторов, по сравнению с традиционно используемыми и выпускаемыми промышленностью, является то, что данный генератор представляет собой источник моноэнергетических «меченых» нейтронов с энергией 14,1 МэВ, образующихся в бинарной ядерной реакции $d + t \rightarrow \alpha$ (3,5 МэВ) + n (14,1 МэВ). Локализация траектории α-частицы путем ее регистрации с помощью многопиксельного альфа-детектора, расположенного внутри нейтронной трубки, дает возможность получить однозначную информацию о времени и направлении вылета нейтрона из мишени.

Изучение методики «меченых» нейтронов свидетельствует о том, что использование (α–γ)-совпадений существенно понижает уровень фона (более чем в 200 раз), обусловленного регистрацией γ-детекторами рассеянных нейтронов, что позволяет идентифицировать небольшие количества взрывчатых, наркотических и токсических веществ. Измеренные значения энергетического и временного разрешений системы (α–γ)-совпадений удовлетворяют критериям, предъявляемым к установкам по идентификации сложных химических веществ, базирующихся на использовании метода «меченых» нейтронов.

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Portable Neutron Generator with 9-Section Silicon α-Detector

The characteristics of the portable neutron generator with a built-in α-detector are presented. Based on the «tagged» neutron method (TNM) the generator is being used for identification of the hidden chemical compounds. One of the special features of such generators compared to generators traditionally used and produced in industry is that the generator is a source of monoenergetic «tagged» 14.1 MeV neutrons produced in the binary nuclear reaction $d+t \rightarrow \alpha$ (3.5 MeV) $+n$ (14.1 MeV). Unambiguous information about the time and direction of the neutron emitted from the target can be obtained by recording an α particle by the multi-pixel α-detector placed inside the neutron tube.

The study of the «tagged» neutron method (TNM) shows that the use of the (α–γ) coincidence reduces the gamma background induced by scattered neutrons by a factor of more than 200, which allows the detection and identification of small quantities of explosives, drugs, and toxic agents.

The measured energy and time resolutions of the alpha–gamma coincidence system meet the requirements imposed on facilities for identification of complex chemical agents based on the «tagged» neutron method.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

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INTRODUCTION

Development of a portable neutron generator with a built-in multi-pixel α-detector is needed for a number of important problems such as:

1) Struggle against terrorism;

2) Humanitarian demining;

3) Identification of explosives, drugs and different hazard materials (toxic agents) hidden in different containers;

4) Removal of unexploded ordnance buried in the ground;

5) Exploration of oil, gas, and ore fields.

One of the special features of such generators compared to generators traditionally used and produced in industry [1–3] is that the generator is a source of monoenergetic tagged 14.1 MeV neutrons produced in the binary nuclear reaction $d+t \to \alpha$ (3.5 MeV) $+\, n$ (14.1 MeV). Unambiguous information about the time and direction of the neutron emitted from the target can be obtained by recording an α particle by the multi-pixel α-detector placed inside the neutron tube.

One of the special features of such generators compared to generators traditionally used and produced in industry [1–3] is that the generator is a source of monoenergetic 14.1 MeV neutrons produced in the binary nuclear reaction $d+t \to \alpha$ (3.5 MeV) $+\, n$ (14.1 MeV). Detecting the α particle by the multi-pixel α-detector, placed inside the neutron tube, provides the tagging of the neutron and gives the information about time and direction of the neutron.

The neutron hits the inspected object and induces an inelastic scattering reaction of the $A(n, n'\gamma)A$ type with emission gammas having energies characteristic of each chemical element contained in the object. Recording of characteristic radiation in coincidence with the signal from the α-detector provides information about both the three-dimensional position of the inspected object along the tagged neutron trajectory (by measuring the time interval between the signals from the α- and γ-detectors) and the energy of this radiation.

The tagged neutron method (TNM) was studied in [4–14] (sometimes it is called Associated Particle Imaging method). In [12–14] it was shown that the use of (α–γ)-coincidence reduces the background, arising from scattered neutrons and induced gammas, by a factor of more than 200, that allows identification of small quantities of explosives, drugs, and toxic agents.

Further development of the TNM method, transition from prototype to production equipment practically use for fulfilling the above tasks mainly depends upon the level of the radiation safety of the equipment. This is especially important for fulfilling the tasks requiring minimization or complete elimination of risk of radiation contamination of inspected objects and environment, including extraordinary situation, for instance, unauthorized explosion of the inspected object. Inspection equipment installed in airports, customs terminals, and other crowded check points should meet such requirements.

Tritium inside the generator (needed for production of 14.1 MeV neutron) makes it impossible to use neutron generators with external system for pumping gas from the tube volume, i. e., requires to use of the so-called «sealed» neutron tube with the internal system for pumping and filling the operating gas. Problems concerning the development of such tubes were earlier solved as a whole. Building an α-detector into the tube greatly complicated manufacture of such tubes because it required both development of special α-detector resistant to various kinds of adverse exposure, including high temperature, and radical changes in the design of the tube and technology for its manufacture to ensure reliable operation within 1000 h and more.

In 2002, we have developed a portable neutron generator [1] with an α-detector based on four optically isolated scintillators. Cerium-activated yttrium aluminate crystals $YAlO_3$ (YAP(Ce)) $10 \times 10 \times 0.5$ mm in size were used as scintillators. Crystals of the α-detector were optically coupled with HAMAMATSU R1635 photomultipliers placed outside the generator housing.

Figure 1 shows circuit of gas-filled tube with built-in α-detector.

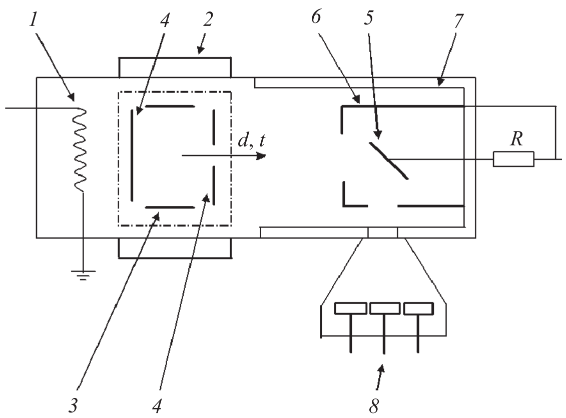

Fig. 1. Schematic view of the gas-filled neutron tube with the α-detector. *1* — deuterium–tritium mixture reservoir; *2* — permanent magnet of the ion source; *3* — anode of the ion source; *4* — cathodes of the ion source; *5* – target; *6* — suppressor electrode; *7* — high-voltage isolator; *8* — α-detector

The gas-filled tube uses Penning's ion source. The operating gas (deuterium–tritium mixture) is contained in a special reservoir – replenisher. The operating gas is released as a result of deuterium and tritium thermal desorption when the leaker is heated (while electrical current passes through the leaker). Deuterium (D^+, D_2^+) and tritium (T^+, T_2^+) ions produced in the source as a result of gas discharge gain energy in the accelerating gap of the neutron tube and bombard target previously saturated with deuterium and tritium. Monochromatic 14.1 MeV neutrons are produced in the dt-reaction.

Since a deuterium and tritium mixture is used as an operating gas of the accelerating tube, the target continuously recovers its properties while the generator operates («self-saturation» by accelerated deuterium and tritium ions which provide stable neutron output in the course of operation of the neutron generator). The beam current of deuterium (D^+, D_2^+) and tritium (T^+, T_2^+) ions may be within 60–120 μA. The target is electrically isolated from the ground and have a potential –80 kV which may vary. A system for suppression of secondary electrons emmited from the target is used to decrease the α-detector background loading and to increase the ion component of the tube current. A voltage multiplier is used as a source of high voltage. The neutron generator is powered from a special unit providing 200 V DC at a current of 100 mA. The neutron generator housing is a stainless steel cylinder $\sim$ 230 mm in length and 72 mm in diameter. The housing walls are 1 mm thick. The tritium target is a layer of hydride-forming material evaporated on a metallic substrate; the target is placed at 45° with respect to the accelerated ion beams of deuterium and tritium (Fig. 1).

The portable neutron generator [1] with an α-detector based on four optically isolated scintillators has provided the intensity of the neutron flux of $5{\cdot}10^6$ s^{-1}. This low intensity is due to rather large background loading of the α-detector (YAP(Ce)) caused by recording of accelerated secondary electrons and bremsstrahlung resulting from interaction of accelerated secondary electrons with the generator housing wall by the α-detector.

In 2003, we have developed a neutron generator with a silicon α-detector consisting of two 8 $\times$ 8 mm pixels to improve neutron generator specifications and to increase the neutron flux intensity. Except for the α-detector, the design of this neutron generator has no differences from the previous design. The intensity of the neutron flux of this generator was $5{\cdot}10^7$ s^{-1} at the beginning of the operation. It is decreased to $\sim$ 10^7 s^{-1} after 650 h of operation.

A neutron generator with a 9-pixel silicon α-detector has been developed by us in 2004–2005. The size of each cell was 10 $\times$ 10 mm. The α-detector matrix is placed 62 mm away from the target center (the solid angle of the α pixel is $2{\cdot}10^{-3}$). Sizes of other components of this generator and two previous designs are the same. Figure 2 shows exterior view of the portable neutron generator with a 9-pixel α-detector. The increasing of the pixel number in the silicon α-detector leads to the improving of the spatial resolution and allows one to receive the information about the structure of the background caused by shielding materials surrounding the investigated object.

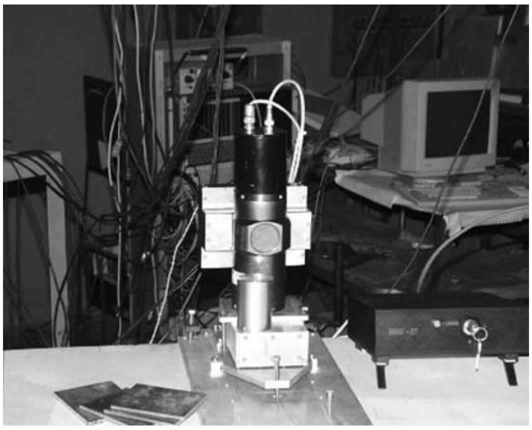

Fig. 2. Portable neutron generator with a 9-pixel α-detector

The 14.1 MeV neutron generator with 9 pixels in α-detector allows 9 beams of tagged neutrons to be produced.

The developed neutron generator has the following main characteristics:

Maximum neutron flux	$5{\cdot}10^7$ s^{-1}
Neutron energy	14.1 MeV
Operation mode	continuous
Maximum accelerating voltage	80 kV
Power supply	200 $\pm$ 10 VDC
Maximum power consumption	30 W
Neutron unit dimensions	145 $\times$ 215 $\times$ 300 mm
Neutron unit weight	$\sim$ 6 kg.

Neutron generator control is completely automated. The high-voltage source is an individual module fastened to the neutron tube butt end from the side of the high-voltage lead-in.

Figure 3 shows the exterior view of the 9-element alpha-detector assembly. The alpha-detector contains:

- a planar silicon detector (crystal)
- a housing of stainless steel
- a ceramic printed board-holder.

The planar silicon detector consists of 9 pixels and forms a 3 $\times$ 3 matrix with a sensitive area 30 $\times$ 30 mm^2. All 9 pixels of the alpha-detector are manufactured on the single plate. Size of one pixel is 10 $\times$ 10 $\times$ 0.3 mm^3.

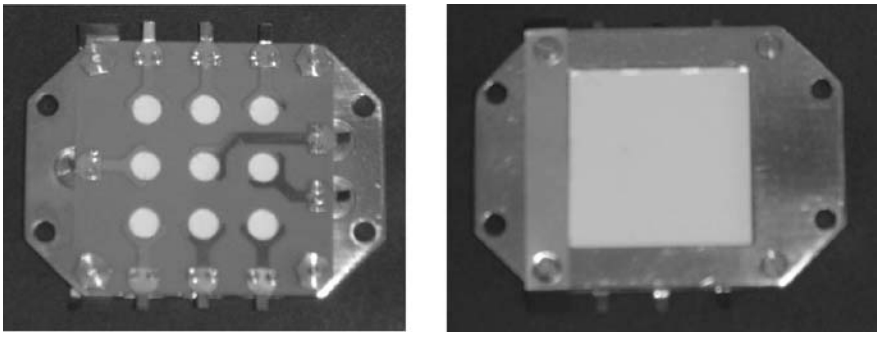

Fig. 3. 9-pixel alpha-detector viewed from the back and from the tritium target side

The stainless steel housing and the ceramic printed board-holder are intended for mechanical protection of the alpha-detector and for providing electric contact with the detector.

A spatial neutron distribution in 9 tagged beams has been measured in the XY plane perpendicular to their direction Z. The measurements were carried out by a 10×10 mm plastic scintillation counter, connected in coincidence with the corresponding alpha-detector pixel. The scintillation counter was moved along the X and Y axes. The distance from the tritium target center to the XY plane was 620 mm.

Figures 4 and 5 present spatial distributions corresponding to a fixed abscissa X and ordinate Y.

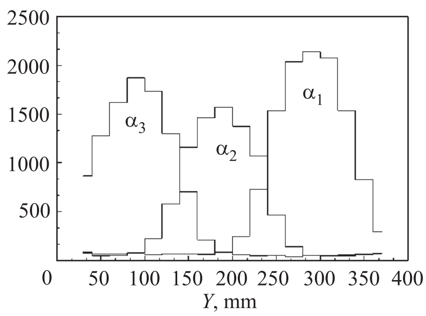

Fig. 4. Spatial neutron distribution in tagged beams corresponding to alpha-detector pixels 1, 2 and 3 (along the Y axis)

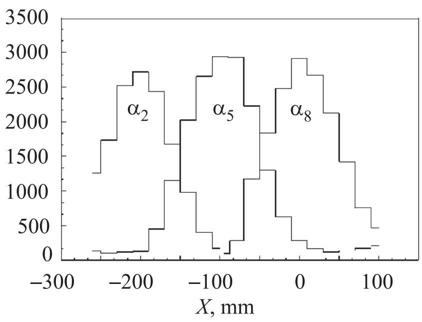

Fig. 5. Spatial neutron distribution in tagged beams corresponding to alpha-detector pixels 2, 5 and 8 (along the X axis)

3	6	9
2	5	8
1	4	7

Numbering of alpha-detector pixels corresponds to the following order (view from tritium target side)

Spatial neutron distributions measured for all 9 tagged beams are well-agreed with the Monte Carlo simulations.

Figure 6 shows the energy spectrum of events recorded by the α-detector (pixel 3) approximated by a function which is the sum of a Gaussian and a cubic polynomial.

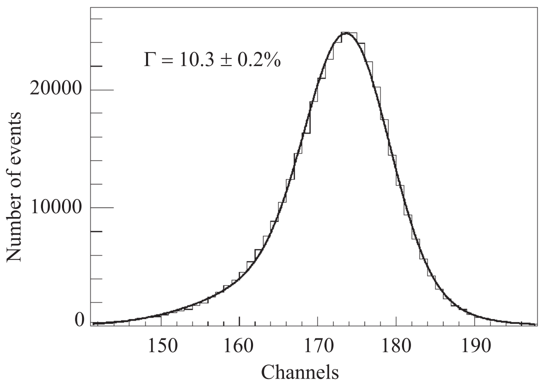

Fig. 6. Amplitude spectrum of events recorded by α-pixel 3 without coincidence with the signal from the gamma-detector

We have used the produced neutron generator and the BGO crystal γ-detector to measure the parameters of the (α–γ) coincidences used in the TNM. Figure 7 presents the energy spectrum of characteristic γ-radiation ($E_\gamma = 4.43$ MeV) detected by the BGO crystal ($\varnothing$ 100 mm, thickness 70 mm; deexcitation time $\sim$ 300 ns) γ-detector in coincidence with the signal from alpha-pixel 3. The spectrum was obtained in irradiation of a ^{12}C sample (10 $\times$ 10 $\times$ 10 cm) placed in the tagged neutron beam corresponding to alpha-pixel 3.

As seen from Fig. 7, this distribution is characterized by two peaks in the spectrum: a peak of total gamma-energy absorption ($E_\gamma = 4.43$ MeV) and a peak ($E_\gamma = 3.92$ MэB) corresponding to a leakage of one of the annihilation gammas ($E_\gamma = 0.511$ MeV) after electron–positron pairing. The energy resolution of the gamma-detector for the $E_\gamma = 4.43$ MeV line is (5.5 $\pm$ 0.2)%.

Analogous spectra of characteristic gamma-radiation were recorded for the ^{12}C sample successively placed in each of 9 tagged neutron beams. It is necessary to emphasize that all the measured energy distributions corresponding to each of 9 alpha-pixels have the same shape.

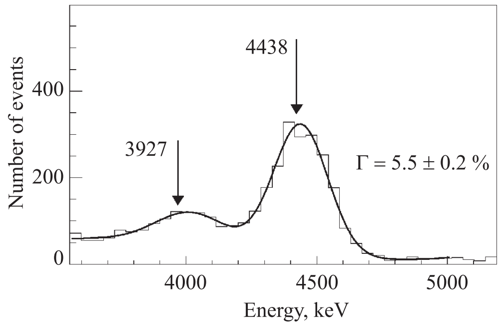

Fig. 7. Energy spectrum of events recorded by the gamma-detector (in coincidence with the signal from alpha-pixel 3) in irradiation of a ^{12}C sample with a tagged neutron flux

The time resolution of (α–γ) coincidence were determined too. Figure 8 presents the time spectrum of (α–γ) coincidences recorded in irradiation of the

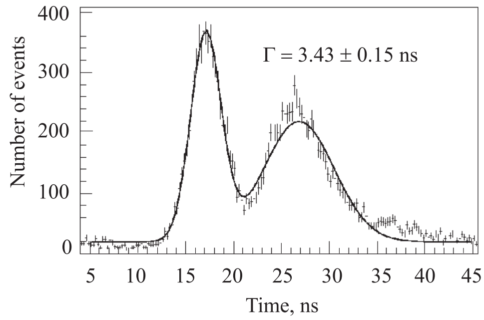

Fig. 8. Time (α–γ) coincidence spectrum recorded in irradiation of the $10 \times 10 \times 10$ cm^{3} ^{12}C sample with the 14.1 MeV neutron flux. The solid line is a result of fitting

^{12}C sample with the tagged neutron flux corresponding to the alpha-pixel 3. This distribution was approximated by the sum of two Gaussians and a constant. The first peak corresponds to characteristic nuclear gammas emitted by ^{12}C, the second peak corresponds to the recorded scattered neutrons. The flat background corresponds to the random coincidences. The time resolution of the alpha–gamma coincidence system is found to be $\Gamma = 3.43 \pm 0.15$ ns.

It is necessary to emphasize that the time resolution of the system for recording coincidence of signals from the alpha-detector and the plastic scintillator (deexcitation time ~ 5 ns) used in the study of the spatial distribution of 9 tagged neutron beams is ~ 1.9 ns.

The measured energy and time resolutions of the alpha–gamma coincidence system meet the requirements imposed on facilities for identification of complex chemical agents based on the tagged neutron method.

Main conclusions of the work could be formulated as follows:

1) The developed 9-pixel silicon alpha-detector allows one to produce 9 independent tagged neutron beams with the needed spatial distribution. It is able to sustain more than 1000 h work with the neutron flux intensity 10^8 s^{-1} without deterioration of the time and energy resolution.

2) The developed portable 9-pixel neutron generator meets all requirements to its design. The expected lifetime of the generator is $\sim$ 1000 h at neutron flux intensity $\sim 3{\cdot}10^7$ n/s.

3) The described neutron generator can be successfully used for solving many important problems listed in the introduction.

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