NEUTRON GENERATORS AND DAQ SYSTEMS FOR TAGGED NEUTRON TECHNOLOGY

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At the T(d,n)He4 reaction each 14 MeV neutron is accompanied by a 3.5 MeV alpha- particle emitted in the opposite direction. A position- and time-sensitive alpha-detector measures time and coordinates of the associated alpha particle which allows determining time and direction (tags) of neutron escape. The tagged neutron technology is based on a time and spatial selection of events that occur when a tagged neutron moves through the object. The VNIIA ING-27 neutron generators produce intensive beams of tagged neutrons in a wide cone angle with the high spatial and time resolution of tagged neutrons provided by the pixelated fast alpha-detector. Requirements to a DAQ system for various tagged neutron devices are reported. The architecture and parameters of the DAQ system based on preliminary online selection of signals by analog front-end electronics and transmission of only useful events for subsequent computer processing are considered. The examples of tagged neutron devices for various applications are discussed.

Keywords: neutron generators, DAQ, alpha-detector, gamma-detector, tagged neutron technology

1. Introduction

Neutron analysis is in great demand in many areas of science and industry. It is due to unique neutron properties such as high penetrability because of zero electric charge and selective interaction with nuclei of chemical elements regardless of their chemical or aggregate state.

Neutron analysis is based on the measurement of secondary gamma-neutron radiation generated as a response to initial neutron radiation. One of the main problems here is a high background caused mostly by gamma rays generated while interactions of neutrons with the components of the device or surrounding objects, by products of the decay of generated radionuclides, etc. In recent years, the Nanosecond Tagged Neutron Technology (NTNT) has been rapidly progressing. Owing to spatial and time selection of events the NTNT allows the level of background radiation to be substantially reduced [1].

Figure 1 displays a block diagram of a typical NTNT device. Initial energies and directions of a neutron and an alpha-particle from T(d, n)4He reaction are unambiguously interrelated. A position-sensitive (multipixel) alpha-detector produces a time-stamp $T\alpha$ and coordinates of the recorded alpha-particle, thus providing its motion direction and the exit time by correction for the alpha-particle velocity. Using this data one can evaluate the neutron exit time, vector of motion, and energy in the direction towards an interrogated object, i.e. the neutron can be "tagged" by the associated alpha-particle recorded. This technology is also known as Associated Particle Imaging (API) due to a significance of the associated alpha-particle for tagging the neutron.

While inelastic scattering of fast neutrons by nuclei, the energy spectrum of the resultant gamma rays has pronounced signatures, i.e. it is unique for different chemical elements, and can be used for their identification. A gamma-detector measures the energy and time $T\gamma$ of arrival of the gamma-quantum. A distance L from the target of the neutron generator to the point of emission of a gamma-quantum generated while inelastic scattering of the fast tagged neutron can be determined by means of measuring the time interval Δt between time stamps of detection of the gamma-quantum and alpha particle associated with the neutron, $\Delta t= T\alpha- T\gamma$. Knowing the distance L and vector of neutron motion, one can calculate the location of the nucleus emitted the gamma-quantum.

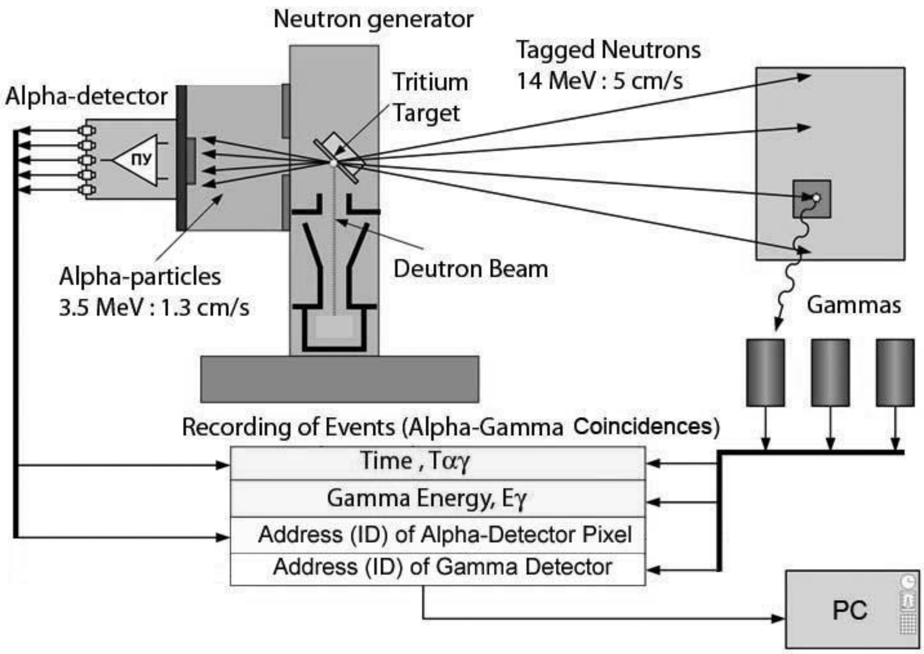


Figure 1. Block diagram of NTNT device

For analysis of bulk inhomogeneous objects, the interrogated object can be conditionally divided by separate elementary volumes (voxels). A position of each voxel can be defined in spherical-like coordinates represented by coordinates of the activated pixel (giving the vector of escape of the tagged neutron) and the time interval Δt between detection of the gamma-quantum and alpha particle. A chemical composition within the voxel is assumed to be uniform. A size of the voxel is determined by the spatial and time resolution of the tagged neutron device. It can be as low as 5-8 cm along the tagged neutron beam and 2-3 cm in transverse direction. An aggregate of voxels gives a 3D map of chemical composition of the interrogated object.

The possibilities of time and spatial selection of events stipulates following advantages of NTNT compared to other methods of neutron analysis:

- 3D imaging of interrogated object;
- High effect/background ratio.

NTNT is a very convenient tool for study of fast neutrons interaction with different nuclei. It was used for measuring angle correlations of products of inelastic scattering of fast neutrons in numerous works. Currently, a cycle of experiments for study (n, n′γ) and (n, 2n′) reactions is run at theTANGRA setup (Figure 4) in the Joint Institute for Nuclear Research (JINR), Dubna, Russia [2]. The results of experiments can be essential for nuclear physics and astrophysics.

The NTNT capability to measure gamma-spectrum at any specific point of the interrogated volume and high penetrability of fast neutrons and gamma-rays make it possible to locate and identify suspicious items in bulk objects or identify items shielded by massive walls or even thick water layer. In mine industry, it allows detecting large (the expected sensitivity is close to 5 karat) diamonds in kimberlite ore before the crushing stage [3]. It simply detects excess carbon at a particular point of the kimberlite sample. The carbon spectrum is characterized by 4.44 MeV and first escape 3.93 MeV peaks. These lines are rather weak in the spectrum of pure kimberlite.

The most promising applications of the NTNT are certainly connected with the remote detection of explosives [1]. Practically all explosives feature higher (more than several times) nitrogen concentration compared to harmless nitrogenated materials such as wool, polyurethane, and nylon. Moreover, ratios of concentration of carbon, nitrogen, and oxygen nuclei in high explosives are within rather narrow range. The NTNT capability to detect key chemical elements C, N, and O increases probability of explosives detection compared to technologies based on only nitrogen determination [4]. In addition, when a substance is identified based on several elements, it is possible to normalize their concentration (for example calculate C/(C+N+O), N/(C+N+O), O/(C+N+O) ratios), which is very important in case of strong neutron and gamma-ray attenuation in bulk objects.

2. Generators of tagged neutrons

A key component of NTNT is a neutron generator with a built-in position sensitive alpha-detector. Currently, off-the-shelf generators of tagged neutrons are manufactured by Thermo Scientific, USA (API-120 series [5]), Adelphi Technology Inc., USA (DT108API) [6], and Dukhov Research Institute of Automatics (VNIIA), Russia (ING-27 series) [7]. Peak intensity of API-120 is as high as $2\cdot10^7$ 1/s. Peak intensity of DT108API and ING-27 is close to $1\cdot10^8$ 1/s. The scintillating alpha-detectors are used in API-120 and DT108API neutron generators. Typically, the scintillator is coupled through an optical plate with a position-sensitive PMT, and the crystal geometry depends on the PMT input window geometry. However, there are only few models of position-sensitive PMT that can be used for this task. Hamamatsu H8500 and H9500 have the largest size of input window (52x52 mm) among them. Assembling of several position-sensitive PMT at the input flange of the neutron generator to increase the sensitive area of alpha-detector heavily complicates the problem.

VNIIA produces specialized silicon and GaAs semiconductor-type detectors for NTNT neutron generators (ING-27). They have certain technological and economical advantages over scintillating alpha-detectors, providing at the same time similar basic operating parameters (radiation hardness, time resolution, detection efficiency). It makes possible to assemble any reasonable configuration (Figure 2) of the alpha-detector limited only by a geometry of a neutron generator flange. A tagged neutron beam profile that defines NTNT angular resolution depends on the pixel size, diameter of deuteron beam spot on the target, and distance between the target and the pixel. Limiting angular resolution is determined by chromatic and geometry ion-optic aberrations, effects of alpha-particle scattering in the tritium target and neutron scattering in the target holder; and in case of ING-27 it is close to 0.04 – 0.05 rad.

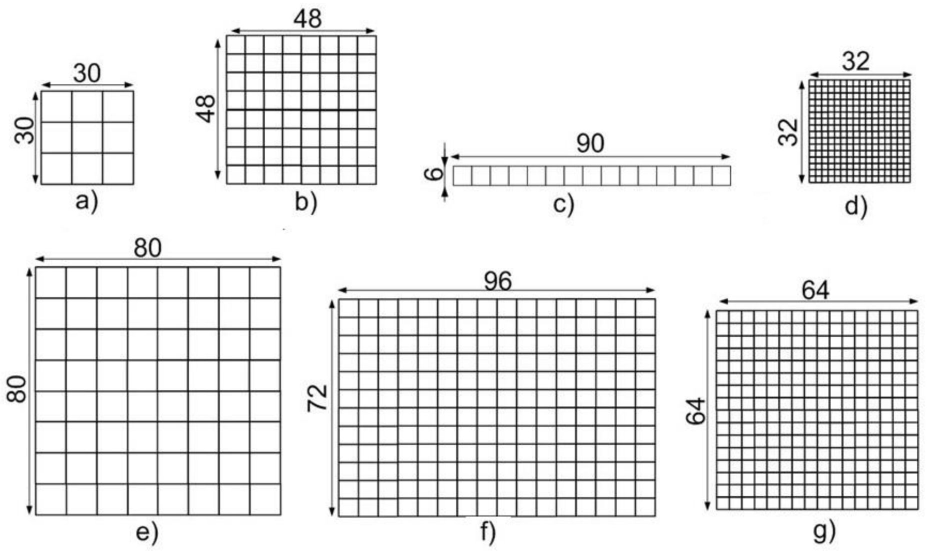


Figure 2. Configurations of semiconductor alpha-detectors to be built-in ING-27 neutron generator: a) 3x3 pixels, 10x10 mm pixel size, b) 8x8 pixels, 6x6 mm, c) 1x15 pixels, 6x6 mm, d) 16x16 pixels, 2x2 mm; e) 8x8 pixels, 10x10 mm, f) 12x16 pixels, 6x6 mm; g) 16x16 pixels, 4x4 mm

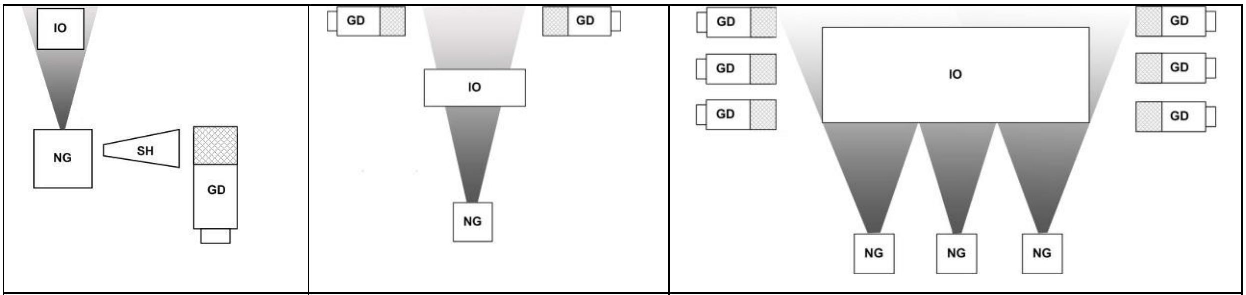
The signal from the alpha-detector pixel is used as a time stamp for measuring the distance ***L*** from the target of the neutron generator to the point of emission of a gamma-quantum (by the time interval Δt). An accuracy (time resolution) is determined by the signal front slope, its fluctuation, and signal/noise ratio. These parameters are deteriorated with the pixel area, and a time resolution of the alpha detector varies from 0.7 ns (Figs 2a- 2d configurations) to 2,5-3 ns (Figs 2e- 2g configurations).

3. DAQ systems for tagged neutron devices

Taking into account a diversity of types of interrogated objects (from mail parcels and mobile phones to cargo containers and vehicles) and applications of NTNT, different NTNT systems can be suggested. They can be roughly divided into several types:

- Mobile systems for detecting mines, for inspection of unattended and suspicious objects, and etc. The sounding by tagged neutrons and measurement of induced gamma-rays are carried out from one side (Figure 3a). The mobile systems include 1 to 4 gamma-detectors. Over hundred of these systems based on 9-pixel ING-27 neutron generator are currently used in the Moscow Metro for control of suspicious objects [8].
- Stationary systems for explosives detection in a baggage and a hand luggage. The interrogated object is located between the neutron generator and gamma-detectors, which quantity varies from 6 to 12 (Figure 3b).
- Stationary systems for prospecting of diamonds in kimberlite ore, control of cargo containers and vehicles. Gamma-detectors are aside the tagged neutron beam axis (Figure 3c). A total number of gamma-detectors is several dozen pieces. Efficiency can be improved by means of usage of several neutron generators and/or a movable neutron generator that is set in motion along a rail by a step motor.

The counting rate of events for the first and second types of NTNT devices does not exceed several thousands 1/s. There a number of relevant DAQ systems developed in various laboratories that can provide the efficiency, energy and time resolution required for practical applications [8]. For the third type, the total counting rate of alpha- detector can be more than $5 \cdot 10^6$ 1/s, the counting rate of each gamma-detector is above 10^5 1/s, and the total rate of events can exceed $(1\text{-}2) \cdot 10^5$ 1/s .The processing of such data stream without loss and distortion of information is a challenge to a DAQ system.



a) b) c)

Figure 4. Types of NTNT systems: a) Mobile system, b) Stationary system for baggage and hand luggage control, c) Stationary systems for control of cargo containers and vehicles. IO – interrogated object, SH – shielding, NG – neutron generator, GD – gamma-detectors.

At present, there are two approaches to the problem of processing signals from NTNT devices: (1) signal processing by analog front-end electronics, preliminary online hardware selection of signals by several criteria (time, amplitude, overlapping) and transmission of only useful events to a PC, and (2) complete digitization of signals from all detectors, and transmission of the data stream to an intermediate computer for subsequent processing.

The NTNT devices implementing digitization of signals from all the detectors have a sampling period as low as 7 − 10 ns. Very short signals from the detectors should be extended in time up to several dozen ns to provide significant number of samples for time and amplitude measurements. It may limit maximum signal rate.

For the analog front-end electronics, the main selection criterion is the presence of signals from alpha- and gamma-detectors within the preset time window and amplitude ranges in the absence of overlapped events. These principles were assumed as a basis for the NTNT data acquisition system developed in VNIIA. The basic features of this system are as follows.

1. Timing is executed by a constant fraction discriminators (CFD) which parameters (fraction, delay) are adjusted for the specific parameters of signals. The time interval Δt between recording the gamma-quantum and alpha-particle is measured by a time-digital converter (TDC).

2. The TDC is initiated by the gamma-detector signal, though in a real life an alpha-particle is recorded prior to the gamma-quantum. For that the signal of alpha-particle is transmitted through a delay line and used as a STOP signal for TDC. It sufficiently reduces a triggering rate of TDC.

3. The useful events (alpha-gamma coincidences) are represented by 8 bytes containing the codes of amplitude of gamma-detector signal, Δt time interval, number of the actuated pixel of the alpha-detector, and number of the actuated gamma-detector. They also include a code of time from the start of operation for study of dynamic objects. The events are transmitted to the computer as a buffered data. The spectra of gamma-signals accumulated simultaneously regardless of coincidences is also measured. It allows calibrate the gamma-detectors on-line by specific peaks of the gamma-spectra.

4. The system is based on modular approach; the modules are bonded through a backbone bus. The typical configuration includes one 32-channel module for alpha-detector and the required number of 6-channel gamma-detector modules.

5. All channels of gamma- detector modules are independent and can record signals simultaneously.

The time for processing of each event does not exceed 2 μs, the maximum rate of events transmission is not less than 200 000 1/s for each gamma-detector module. A real required rate of events is much less for any NTNT system. The achieved time resolution is as low as 1.0 − 1.2 ns for fast LYSO and LaBr3 detectors, and 1.5 – 3.0 ns for relatively slow NaI(Tl) and BGO gamma-detectors .

To diminish impact of overlapping of signals from alpha-detector, the time window for recording the alpha-gamma coincidences can be changed by size and can be shifted by means of hardware and software with the accuracy of 1 ns. Thus the time window can be adjusted to the position of interrogated object along the tagged neutron beam. This is especially important for the task of diamonds detection in kimberlite ore when the interrogated zone is restricted by a sampling tray. A reduction of the time window decreases background.

4. Conclusion

The detecting equipment developed for the tagged-neutron technology ensures precise and stable measurements of the event parameters at any reasonable recording rate of events and number of gamma-detectors. It meets the requirements for the practical realization of the tagged-neutron technology for various applications, including explosives detection in a baggage and a hand luggage, control of cargo containers and vehicles, prospecting of diamonds in kimberlite ore.

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