Using Neutron Generator with APT/NNA for Detection of Explosives

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Abstract. Nanosecond Neutron Analysis (NNA) method with spatial selection of secondary gamma-radiation, proposed at V. G. Khlopin Radium Institute as a further development of the well-known Associated Particle Technique (APT), allows one to substantially (by two orders of magnitude) reduce the level of the background radiation, making possible creation of devices for detection of small amounts of hazardous materials. A prototype APT/NNA device is based on a DT neutron generator with built-in nine-segment semiconductor detector of accompanying alpha-particles. The prototype is the basis for further development of the NNA method in order to create devices for detection of explosives and other hazardous materials in luggage, sea cargo containers, etc. A concept of a device for detection of hazardous materials in sea cargo containers "3D NNA Scanner" has been developed. Results of numerical modeling suggest, that the device will be capable of detecting 30 kg of explosives hidden anywhere inside a 40-feet cargo container within a 12 minute-long inspection cycle.

1. Introduction

The main problem encountered in the non-destructive analysis of materials by neutron methods is a very high counting rate in the secondary radiation detection channels, caused by interaction of probing neutrons with the materials of the neutron source, the inspected object, and the materials of the environment. The resulting very high level of background has until recently ruled out a wide use of neutron-based methods for detection of small amounts of hazardous materials hidden among other objects in passenger luggage, cargo containers, etc.

The Nanosecond Neutron Analysis (NNA) method with spatial selection of secondary gamma-radiation, proposed at V. G. Khlopin Radium Institute as a further development of the well-known Associated Particle Technique (APT) [1], allows one to substantially (by two orders of magnitude) reduce the level of the background radiation, making possible creation of prototype devices for detection of small amounts of hazardous materials [2, 3].

The method is based on irradiation of the inspected object or volume with fast neutrons and detection of characteristic prompt gamma-rays from inelastic neutron scattering reactions. The background suppression is achieved by equipping a deuteron-tritium (DT) neutron generator with a built-in position-sensitive detector of alpha-particles, which accompany neutron emission, and detecting characteristic gamma-rays within a narrow time interval, counted from the moment of detection of each alpha-particle. Only those gamma-rays that are produced in reactions of 14 MeV neutrons in the area of interest are accepted by the data acquisition system (they coincide with alpha-particles), while those produced in the surrounding material (or of cosmic origin etc.) are suppressed (they do not coincide with alpha-particles).

Each of the nine "pixels" of the alpha-particle detector corresponds to reactions of 14 MeV neutrons in a separate region of space ("in-plane" position resolution). A 3×3 matrix of 1 cm^2 alpha-detectors corresponds to nine 8×8 cm^2 areas at 50 cm from the target of the neutron generator (NG).

Time of arrival of each gamma-quantum relative to the corresponding alpha-particle (which accompanied the 14 MeV neutron that produced this gamma-quantum) allows one to distinguish between objects located at different distances from the target of the neutron generator ("in-depth" resolution). Every 1 ns time-of-flight of the 14 MeV neutron means, that it reacts at ~5 cm further from the NG target. Thus, "in-plane" position resolution due to "pixelization" of the alpha-detector is complemented by "in-depth" resolution due to time-of-flight measurement.

2. Prototype NNA/APT Device

A prototype APT/NNA device (FIG. 1) is based on a DT neutron generator with built-in nine-segment semiconductor detector of accompanying alpha-particles. The neutron generator NG27 was produced at the All-Russian Research Institute of Automatics, Moscow[1]. It produces up to 5×10^{7} 14 MeV neutrons per second (into 4π). The nine-segment detector of accompanying alpha-particles was produced by APSTEC Ltd., St.-Petersburg[2]. It is a 3×3 matrix of 1 cm^2 semiconductor detectors equipped with the appropriate electronics, which determines the detection time of each alpha-particle and the number of the hit segment. The geometrical efficiency of the alpha-detector is about 2%, and its intrinsic efficiency to 3 MeV alpha-particles is close to 100%.

FIG. 1. Prototype device based on neutron generator with built-in nine-segment associated particle detector and BGO-based gamma-ray detector (in front), and portable digital electronics (behind).

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[1] www.vniia.ru
[2] www.apstec.ru

The current version of the prototype includes one or two gamma-detectors based on ∅2.5”×2.5” BGO crystal and Hamamatsu R6233-01 photo multiplier.

The prototype is serviced by a custom-made electronics, which includes the following components (see FIG. 1):

- Alpha-detection module, which can handle count rates up to 10^7 α/s with dead time depending only on signal’s length.
- Gamma-detection module, which can handle count rates up to 10^6 γ/s per second from a BGO-based gamma-ray detector.
- PC-controlled HV power supplies for photo multipliers used in gamma-ray detectors and for the position-sensitive associated particle detector.
- Single-board PC.
- Data transfer interface module.
- System indicator module.

All parameters of the device can be controlled remotely, using a standard RF network connection.

The data acquisition system is based on fast flash-ADCs, programmable logic devices (PLD) and digital signal processors (DSP), which perform on-line correlation analysis of signals from BGO-based gamma-detectors and from the nine-segment alpha-detector. This approach allows one to preserve good energy- and time-resolution at very high counting rates: more than 10^6 α/s and more than 10^5 γ/s. Time resolution of the alpha-detector – gamma-detector pair is FWHM = 1.7 ns (for 4.43 MeV ^{12}C line), which corresponds to about 8 cm “in-depth” position resolution.

3. Experimental Results with Prototype Device

Experiments were carried out with specially prepared imitators of different explosives and some non-explosive materials. These imitators correctly reproduced relative concentrations of carbon, nitrogen and oxygen in the following explosives: RDX, TNT, C4, nitroglycerine, and PETN. Other samples of non-explosive materials were sugar (the same C/O ratio as in TNT) and melamine (a very nitrogen-rich substance). Mass of each imitator was 300 g, and they were sealed inside 24 g aluminum cans.

For each detected gamma-quantum the following information is stored:

- its energy;
- its time-of-flight relative to the associated alpha-particle;
- number of the hit segment of the nine-segment alpha-detector.

This information is enough to construct a separate energy spectrum for each 3D “voxel” of the sensitivity zone of the device with resolution about $8\times8\times8$ cm^3.

Example of energy spectra measured in 120 seconds for RDX imitator and sugar are shown at FIG. 2. The counting rate of gamma-rays from 300g imitators that are accepted by the data acquisition system was about 6 s^{-1} (in the energy range from 2 MeV to 8 MeV). The corresponding counting rate of the background was about 5 s^{-1}.

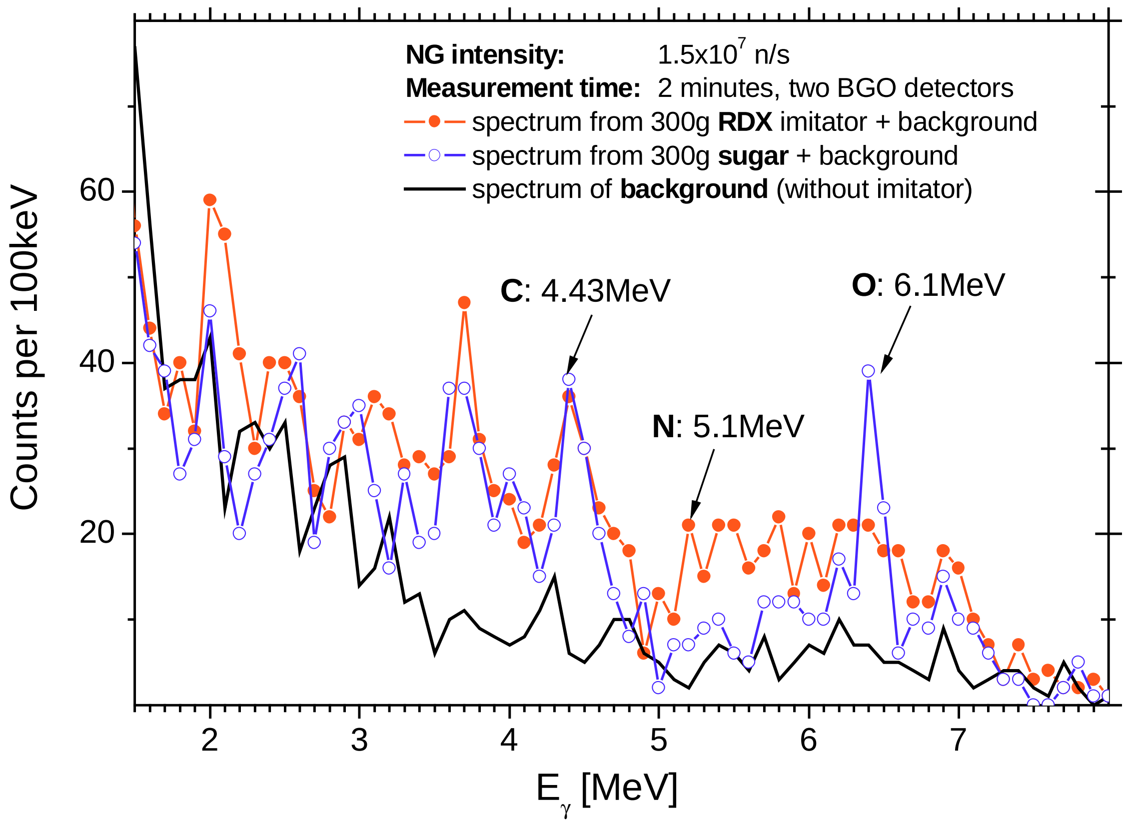

FIG. 2. Example of spectra measured for 300g RDX and sugar imitators, and spectrum of the background (without samples in the sensitive area).

Since the distance from the inspected object to the NG target is generally not known (e. g. when one is inspecting the content of a closed container), the experimental data are automatically "scanned" by the data analysis software along the time ("in-depth" distance) coordinate in order to determine, whether any of the nine "in-plane" areas contain candidates for the explosive substance. For example, spectra on FIG. 2. are shown for the "in-plane" area #9 (corresponding to one of the nine segments of the alpha-detector) for distances (40 ÷ 50) cm from the NG target. In two cases (lines with symbols) these "voxels" contained at least part of the 300g samples, while in one case (line) it contained only air. The remaining background (line) comes mostly from accidental coincidences between alpha-particles and gamma-rays. If no NNA/APT were used, this background spectrum would be a factor of 100 higher than on the above figure.

Energy spectra from each "voxel" are analyzed by a combination of non-linear regression method (using response functions to individual chemical elements calculated by MCNP5[3] code), principal component analysis (using calculated responses to different known explosives), and possibly other methods like partial least squares. As a result, one gets a number of characteristics, such as relative concentrations of different chemical elements in different "voxels", proximity of the experimental gamma-spectrum to those of individual explosives, etc. These results are then analyzed by a "fuzzy logic" engine, which makes the decision about the nature of the investigated object. If the collected statistics is not enough to make a definite decision, the "fuzzy logic" engine automatically starts additional measurements.

[3] MCNP — A General Monte Carlo N-Particle Transport Code, Los Alamos National Laboratory.

Measurements with 300 g imitators located at 45 cm from the NG target with 1.5×10^{7} n/s neutron flux yielded typical measurement times about 30-40 seconds, within which the device was able to correctly identify the imitator as either an explosive or a non-explosive. For 1 kg of explosives the detection time would be less than 10 seconds.

Further shortening of the detection time is possible, if one increases the neutron flux from the NG (the present version allows up to 5×10^{7} n/s without severe degradation of the target), and increases the number of gamma-ray detectors (present version of portable fast digital data acquisition electronics allows expansion up to 12 gamma-detectors without any changes).

Characteristics of the existing prototype are listed in Table I.

TABLE I: CHARACTERISTICS OF THE EXISTING PROTOTYPE APT/NNA DEVICE.

Explosives detection limit	100 g in tens of seconds
Detection method	Nanosecond neutron analysis (NNA) with spatial resolution (APT technology)
Decision-taking algorithm	Automatic
Simultaneously inspected area	$30\times30\times30$ cm^3
Spatial resolution	7-8 cm in-plane, 8-10 cm in-depth
Total mass of the device	not more than 20 kg
Dimensions	$70\times45\times20$ cm^3
Radiation safety	Safe when switched-off

3. "3D NNA Scanner" for Cargo Container Inspection

The described prototype is the basis for further development of the NNA method in order to create devices for detection of explosives and other hazardous materials in luggage, sea cargo containers, etc.

These devices will be based on universal module ("NNA/APT basic module") consisting of an APT neutron generator and 12 gamma-ray detectors (see left side of FIG. 3). Each NNA/APT basic module will be able to simultaneously inspect about 1 m^3 volume with spatial resolution needed for the given application. Depending on the geometry of the inspected object several NNA/APT basic modules can be combined to ensure the required inspection time. Alternatively, large objects can be scanned by a single NNA/APT basic module installed on a movable support. Experiments with the existing prototype and MCNP calculations show, that in case of the inspection of a large transport container with six NNA/APT basic modules (see right part of FIG. 3) within about 10 minutes the device will be able to detect about 10 kg of explosives hidden anywhere inside the container filled by 30% with organic (non-explosive) material. If the explosive is located close to the wall of the container, the detection limit drops to about 2 kg.

The inspection device can be optionally equipped with neutron detectors, which would allow simultaneous detection of shielded and unshielded fissioning materials by induced neutron emission.

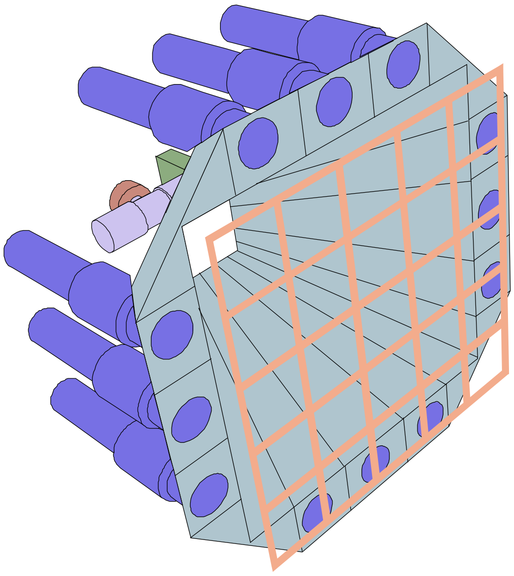
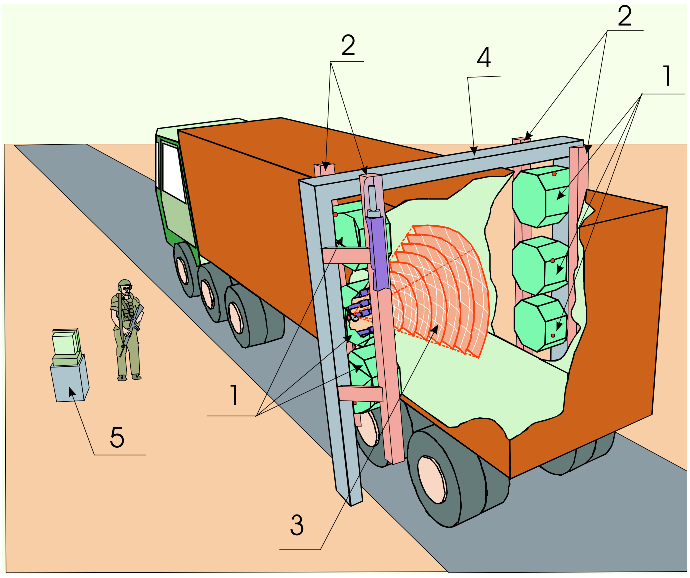

*FIG. 3. **Left:** one NNA/APT basic module consisting of one APT neutron generator and 12 gamma-ray detectors. **Right:** "3D NNA Scanner" for Inspection of Sea Containers. 1 – NNA/APT basic modules. 2 – neutron detectors. 3 – volume inside the 40'-high sea container screened by one "measurement module". 4 – construction frame. 5 – remote control and data analysis module*

In order to estimate the parameters of the NNA/APT device for inspection of containers and to check the results of MCNP calculations, measurements with the existing prototype were carried out. The experimental setup simulated explosives inside a metallic container filled with organic materials. The prototype device was located outside the metallic wall, simulating the wall of the container (see left part of FIG. 4).

*FIG. 4. Measurements with 700g melamine sample. imitating explosive inside a container. The prototype device (**left**) was outside the metallic wall, and the 700g melamine sample (**right**) was placed at about 1 meter from the NG target behind a bag filled with organic materials.*

A plastic bag with 700g of melamine (67% nitrogen, 33% carbon, white plastic bag in the right part of FIG. 4) was placed at ~1 meter from the target of the neutron generator (45 cm from the BGO gamma-ray detector) behind a bag filled with organic materials. Among these materials were wool, cotton, books, soap, electric appliances, melamine, etc.

In order to see the effect from the sample, two measurements were carried out: with and without melamine. Each measurement lasted 5 minutes at NG intensity 1.5×10^{7} n/s. The results were analyzed by non-liner regression procedure, and concentrations of carbon, nitrogen, oxygen, and other elements were simultaneously obtained for spectra, measured in coincidence with each of the nine segments of the associated particles detector at different distances from the NG target.

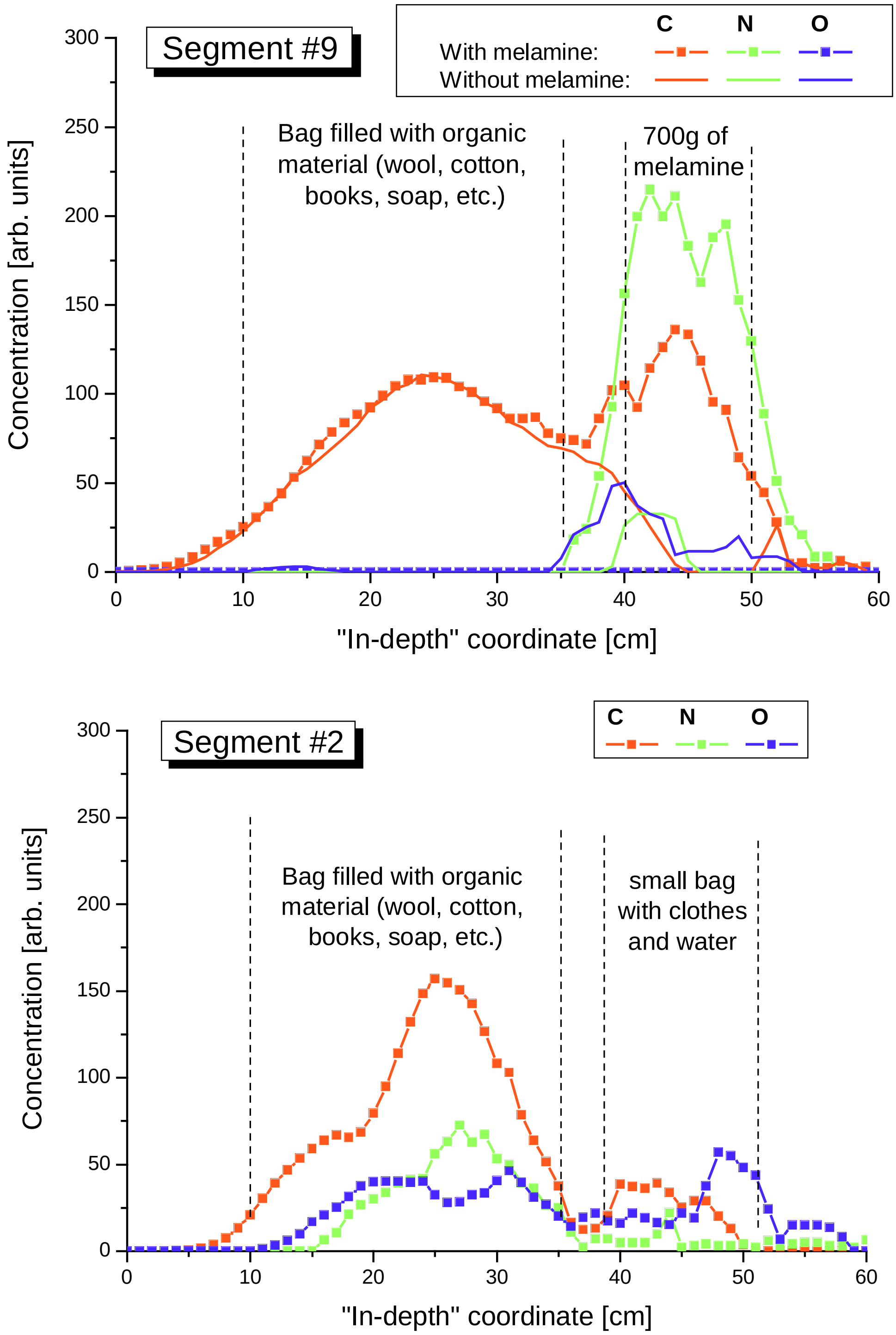

FIG. 5. Distribution of C, N and O along "in-depth" coordinates (counted from the front plane of the BGO detector) in Segments #9 and #2. Results were corrected for the distance from NG target to the given coordinate. Experiment was carried out in the geometry shown at FIG. 4.

FIG. 5 shows examples of distributions of concentrations of C, N and O for alpha-detector segment #9 (which corresponded to the direction towards the melamine sample), and segment #2 (which corresponded to neutron flight path through two bags on FIG. 4). Results were smoothed and corrected for the difference in distances to NG target and BGO detector for different locations along the “in-depth” axis, so the presented concentrations directly correspond to the mass of the material at the given location.

The effect from melamine sample can be clearly seen on the top figure (Segment #9) between 40 cm and 50 cm. The variety of C/N/O relations on the bottom figure (Segment #2) reflects the complexity of the filling of the two bags.

4. Conclusions

Prototype device for detection of explosives, based on Nanosecond Neutron Analysis and Associated Particles Technique (NNA/APT), was shown to be able to detect several hundred grams of concealed explosives within tens of seconds at distances about 50 cm and within several minutes at distances around 1 meter from the NG target.

The fast digital electronics, which is servicing the device, is capable of handling extremely high gamma-ray and alpha-particle counting rates, which allows up-scaling the existing prototype to include up to 12 gamma-ray detector and neutron generator with intensity up to 10^8 n/s without significant changes.

Work is under way to create a full-scale prototype NNA/APT basic module, which can serve as a component for large-scale devices for inspection of cargo containers and luggage.

Acknowledgements

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