Project title: **DENSE PLASMA FOCUS BASED NEUTRON SOURCE FOR DETECTION OF ILLICIT MATERIALS AND EXPLOSIVES BY NANOSECOND NEUTRON PULSES**

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(i) **Scientific scope of the project**

The scientific scope of the CRP project covers:

- Elaboration of main principles of the single-pulse Nanosecond Impulse Neutron Investigation System (NINIS) fitted for a disclosure of hidden objects (explosives in particular including the detection of bulk explosive materials) just by one nanosecond pulse
- Development of the entire system, based on Dense Plasma Focus device as a neutron source, including detectors with nanosecond temporal resolution
- Work on the numerical modeling aspects of the proposed system by use MCNP code
- Providing the “proof-of-principle” experiments to make clear how and where the proposed approach can significantly improve existing methods
- Optimization and validation of probing and detection to establish sensitivity achievable.

The method proposed by us belongs to the wider group of approaches [1, 2, 3a] that makes use of an interaction of neutrons (fast or thermal) with different materials. As a result of such interaction a field of scattered neutrons is formed. This field appears because of elastic and inelastic scattering of primary neutrons by nuclei of the irradiated matter. Besides an induced gamma radiation is emitted from an object under irradiation. The information on elemental composition of the object can be obtained from spectra of both the scattered neutron field and the gamma radiation photons.
The so-called Fast Neutron Scattering Analysis (FNSA) developed lately by Buffler at al. [3a] makes use of a train of nanosecond pulses of fast neutrons having low intensity (of the order of $10^2 \ldots 10^3$ neutrons per pulse, supplied by the Van de Graaff accelerator). The necessary data about a chemical content of the substance under interrogation are obtained from an analysis of a spectrum of the elastically scattered neutrons registered with a help of a photo-multiplier tube with a scintillator (the time-of-flight – TOF – method). The above authors have demonstrated a possibility to determine concentration of the elements H, C, N, and O (very common to different types of explosives) in small (0.2-1.0 kg) samples providing for this goal a few billions of the neutron pulses. The main reasons for production of such a huge number of pulses are the necessity to reach exhaustive statistics at the collection of the recoil protons produced by neutrons within a scintillator and to increase a signal-to-noise ratio to a satisfactory level. Other concepts [3b...g] use low-intensity ($\leq 10^8$ n/pulse) long-pulse (1-10 µs) neutron sources demanding many shots during long interrogation time (from few minutes till half an hour) and resulted in high activation of an object under unveiling.

We proposed [4] to bring into play a neutron source based on a plasma accelerator of the Dense Plasma Focus type (DPF), which generates pulses of neutrons in the nanosecond (ns) range of their durations but having at the same time a very high intensity – $10^8 \ldots 10^{12}$ neutrons per pulse. It gave us an opportunity to provide all measurements in TOF technique by means of a single nanosecond pulse, i.e. during one millionth of a second. Because of unique characteristics of the neutron source the signal-to-noise ratio will be increased just proportionally to the decreased number of shots (e.g. one pulse instead of billions compared with the case of the Van de Graaff source [3a]) whereas neutron fluence necessary to characterize hidden objects will be reduced by 2-5 orders of magnitude compared with [3].

(ii) The results obtained under the CRP within the frame of the project

1. Devices

Our devices, PF-10, currently operating in the A.I. Alikhanov Institute of Theoretical and Experimental Physics (ITEP), Moscow, RF, has the 10-kJ capacitor bank, whereas the PF-6, which is in operation at the Institute of Plasma Physics and Laser Microfusion (IPPLM), Warsaw, Poland, has 7.4 kJ of energy in its capacitor storage (see Fig. 1). They are capable to generate in one pulse of the about 10-ns duration up to circa $10^9$ D-D (2.5-MeV) neutrons or $10^{11}$ D-T (14-MeV) neutrons. These two prerequisites give a principal possibility to create the above-mentioned single-shot “Nanosecond Impulse Neutron Investigation System” (NINIS) intended for an interrogation of hidden objects.
Moreover this DPF-based neutron source is ecologically more acceptable compared with others because it produces neutron radiation only “on demand” for a few nanoseconds (a so-called “push-button device”) and it doesn’t require a special storage as the isotope-based sources. It uses charging voltage of about 10…20 kV only (instead of 150 kV as in neutron generators of direct-type acceleration and several MV as in the case of classical accelerators of the Van de Graaff type). This modern DPF is characterized by several outstanding features such as operation with vacuum-tight (welded) chambers (so it can be treated as “closed, or sealed radiation source” even when using the radioactive deuterium-tritium mixture as a working gas). The life-time of the most sensitive element of the device – its discharge chamber – is of the order of $10^6$ “shots”. It has relatively low size and weight, comparatively low cost, and it obeys an opportunity to work with a high repetition rate (tested up to 15 cps), etc. In our experiments we used pure D$_2$ and D-T mixture as working gases for the DPF.

2. Diagnostics

For registration of direct and scattered neutrons as well as hard X-Rays we used Hamamatsu-1949-51 module, S/N WA5952, FWHM = 3.12 ns, a photo-multiplier tube (PMT) of the type SNFT with different scintillators, FWHM = 2.5 ns, and a special detector based on micro-channel plates MCP-PMT Chevron R3809 U-52 type with time resolution 0.276 ns (Fig. 2).
3. **The method**

Main principle of the technique used [4] is based on the change of the energy of scattered neutrons during high-brightness short-pulse irradiation of an object under unveiling, when their energy *dissimilar* decreases due to *elastic* scattering on nuclei of various elements having *different* masses. It must be reflected in a difference of TOF of these neutrons, i.e. in a respective time delay of pulses of the scattered neutrons in relation to the pulse of primary neutrons produced by DPF. Element’s content (chemical formula) of the interrogated substance (especially nuclei of H, C, N and O, as well as P and some others typical for explosives) can be determined (calculated) afterwards taking into consideration these time lags, the amplitudes of the neutron pulses scattered by corresponding element’s nuclei and the respective cross-sections of the elastic scattering of neutrons, having specified energy, on the nuclei of the particular elements. Additionally we have to take into account TOF of X-Ray photons from DPF chamber till the PMT, time delay of neutron pulse appearance inside the DPF chamber compared with the X-Ray pulse there, geometry of an object, angles of irradiation and scattering plus some uncertainties.

4. **Simulations**

We undertake attempts to simulate scattering of 2.45-MeV neutrons from various objects by means of full MCNP calculations using standard MCNP-5. We used a new version of so called “input”, which takes into account the whole process of neutron scattering by dissimilar objects and allows to model signals registered by virtual detectors with high precision. As an example we present here usage of this MCNP “input” in particular to simulate scattering of neutrons from long objects (here a 1-meter high-pressure aluminium cylinder filled with deuterium at 70 atm. in a scheme shown in Fig. 3a). The energy distribution of “direct” and scattered neutrons is in Fig. 3b whereas the resulting time-of-flight signal is in Fig. 3c.

5. **Tests – “proof-of-principle” experiments**

a) In the first experimental session we investigated scattering of neutrons by a 1-liter bottle of ethanol (C\(_2\)H\(_5\)OH) [4] and methanol (CH\(_3\)OH) positioned in a very close vicinity to the DPF chamber. The geometry of the experiment is shown in Fig. 4. In the first case we use in PF-6 the chamber producing \(10^9\) 2.45-MeV neutrons per shot (\(E_{bank}=7\) kJ) whereas in the second case we operate with the DPF bank energy on the level of about 4-5 kJ with neutron output of the device \(\sim 3\times10^8\) neutrons per pulse. Our scintillator used for the PMT probe had a diameter 10 cm with its length of 10 cm. Our fast channels (photomultiplier tubes with scintillators – PMT+S) had in these experiments temporal resolution 3.12 ns. We used two channels placed in L’=1.0-m and L”=18.5-m distances from the DPF. A typical result
obtained with them for the second case is presented in Fig. 5. The lowest trace is the same as the middle one but taken with the higher sensitivity of the oscilloscope.

Fig. 3 Scheme of numerical experiment (a), energetic distribution (b) and temporal behaviour (c) of neutrons coming to the detector: 1 – direct neutrons (2.45 MeV), 2 – neutrons scattered by aluminium, 3 – neutrons scattered by deuterium

Fig. 4 Scheme of the experiments

Preliminary testing shots made with the PF-6 device (IPPLM) have shown that the hard X-Ray pulse (HXR, photon energy $h\nu > 60$ keV) always has its rise-time shorter than the temporal resolution of our PMT+S channels.
Fig. 5  Oscilloscope traces of PMTs placed at 1.0 and 18.5 meters from the target

At the same time a set of 100 successive shots made simultaneously with two PMT+S placed at 3.5 and 7.5 meters from the DPF chamber in the same direction (along Z-axis) has shown that inside the chamber the neutron pulse follows the HXR pulse with the delay of 8 ns plus/minus 2 ns [4]. And what’s more, the broadening of the same neutron pulse at the distance of 7.5 meters compared to the pulse measured at 3.5 meters shows that the neutron spectrum of our DPF in Z-axis direction has monochromaticity $\Delta E/E \approx 1\ldots3\%$.

In the oscilloscope trace of Fig. 5 for the PMT+S positioned at 18.5-m distance where we used two different sensitivities for two registration channels in the same shot (the middle and lower traces of Fig. 5) a sequence of pulses is seen which demonstrates different energies because of their delay time in relation to the hard X-Ray pulse.

First of all calculation of neutrons’ energy of the first pulse (“$n$”), seen in Fig. 5, by using time-of-flight (TOF) data with the help of formula:

$$E \text{ [MeV]} = (L \text{[m]} / t \text{[ns]})^2 \times 5.23 \cdot 10^3,$$

has shown that their medial energy is $\approx 2.6$ MeV. This value is a typical one for neutrons generated in a DPF in forward direction, i.e. with the small angle in relation to Z-axis of its chamber (“head-on” neutrons). However the so-called “side-on” neutrons generated at the angle 90° to Z-axis of a DPF chamber have energy 2.45 MeV. Now we have to understand what would be the energy of the second and the third neutron pulses (“$n_0$” and “$n_1$”).

To calculate the real position of neutron pulses “$n_0$” and “$n_1$” in the oscilloscope trace and consequently their TOF and energy we have to perform the following procedures:
1) To move to the left on the oscilloscope trace the hard X-Ray pulse by its TOF of 18.5 m (62 ns). It will be the moment of the appearance of the HXR pulse inside the chamber.

2) To move to the right on the oscilloscope trace the above point by 8 ns – it will be the moment for neutrons to top out their maximum inside the DPF chamber.

After the above procedure we shall have the reference point, from which we can calculate all time intervals needed for direct or scattered beams of neutrons to reach our PMT. Taking into consideration that our target is placed at a distance of 20 cm to the DPF chamber’ center and in the “side-on” position, we have to perform all calculations for the neutrons having energy 2.45 MeV and in the conditions that their direct TOF from the centre of the DPF chamber till the target is 10 ns. Effective angle of the bottle’s irradiation was $\theta \approx 10^\circ$.

Kinematics of elastic scattering of neutrons by different nuclei gives the diagram of the dependence of lost energy at collisions in relation to the neutron laboratory scattering angle. It is shown in Fig. 6. Our PMT+S probe was placed at the angle $\alpha$ of about 80° to the direction of the neutron beam passing through the centre of the bottle with methanol. From the graphs of Fig. 7 $a$, $b$ based on kinematics of the scattering and on our experimental geometry one can see that our two peaks on the oscilloscope trace – “$n_0$” (908 - 10 = 898 ns) and “$n_1$” (925 - 10 = 915 ns) – may be attributed to the scattering of the 2.45-MeV neutrons on the oxygen and carbon nuclei accordingly. Uncertainty bars are resulted from time resolution of detectors, from a precision of measurements of the peak’s position on the trace, and due to TOF of neutrons through the bottle. It is seen that in principle scattering on nitrogen nuclei can be distinguishable as well. But what could be the origin of the pulse “$n_2$”?

Fig. 6 Graph showing the ratio of energy of neutrons scattered by nuclei of various elements to the initial energy of neutrons of the irradiating beam in dependence of scattering angle

It appears that it is our high-pressure 10-litre 1-m by height cylinder made by aluminium and filled with deuterium at a high pressure $\approx 150$ atm. It was placed at 1 m from the DPF chamber. It has rather small diameter of about 14 cm and it was positioned vertically (resulted in a short scattering pulse).
Fig. 7  TOF for 18.5 m (a) and energy (b) measurements plotted for the scattering scheme of Fig. 4

This high-pressure cylinder was positioned with the angle between the incident beam and the direction onto the PMT+S close to 90°. To calculate energy of the neutrons scattered upon it we have to subtract first a TOF interval of 2.45-MeV neutrons to reach the cylinder (i.e. 45.8 ns) from the whole value of the pulse’s delay. It gave us the rest value of TOF for scattered neutrons – 1181 ns, energy of these particles – 1.28 MeV, and the ratio to the incident one ≈ 0.524. As for the aluminium nuclei (about 3 time more compared with the number of deuterium nuclei) their peak is exactly coincides with the peak of neutrons scattered by carbon in the bottle and it forms a pedestal for the carbon peak. Kinematics of the process supports this conclusion.

It is interesting to compare cross-sections of 2.45-MeV neutrons, elastically scattered on the above materials, and of 2.6-MeV neutrons – on a 20-cm Teflon cylinder (positioned in the direction of the PMT+S and blocking the “direct” beam of neutrons – see Fig. 1 b). It appears that these figures are equal to 1.5 barns – on nuclei of $^{12}\text{C}$, whereas the related magnitude for $^{16}\text{O}$ in this range of $\sigma(E)$ going to a minimum at 2.35 (relatively narrow) is equal to 0.6 barns at its slope. Cross-sections of elastic scattering on deuterium and aluminium are 2.35 and 2.2 barn correspondingly. For fluorine and 2.6-MeV neutrons it is on the level of 1.5 barns. These figures together with the geometrical factors are very well fitted to the relative ratio for the amplitudes of the peaks “$n$”, “$n_0$”, “$n_1$”, and “$n_2$”.

b) Our next experiment was devoted to the clarification of the restrictions of the method implied by distance and neutron yield of the device. 1-litre bottle with phosphoric acid (H$_3$PO$_4$) was used as a target. Diameter of the bottle was 10 cm. It was installed tightly with the DPF chamber, and the geometry of our experiments was the same as above with $\beta'\approx 35^\circ$, $\beta''\approx 27^\circ$, $L'\approx 2.2$ m, $L''= 8$ cm, $\theta \approx 10^\circ$, $L'''= 7$ m. In these tests we have experienced an opportunity to use much lower bank energy (~2-3 kJ), smaller DPF chamber, and decreased neutron yield (~10$^8$ n/shot) what results in much lower activation of objects under
interrogation and in shorter TOF base as well (2.2 meters). We used here 2 PMT of the SNFT type (2.5 ns time resolution) placed in two different distances from the scatterer in each experiment. In this case the neutron pulse duration detected at a close vicinity to the DPF chamber became 5-8 ns. Thus the longitudinal dimension occupied by the pulse in the direction of its propagation (or a thickness of an almost spherical neutron “shell” spreading from the DPF chamber into space) is about 10-15 cm.

Two typical oscilloscope traces taken at the experiments with a bottle of phosphoric acid obtained from S PMT-1 for two different situations – when direct neutron beam to the PMT-1 from the DPF chamber was almost completely blocked by a screen and conversely when it irradiated a scintillator freely – are shown accordingly in Fig. 8 a and b.

Because the neutron detector signals contain an essential noise component in this our case of low dose of neutrons we used wavelet method suggested by MATLAB Wavelet Toolbox. We used De-noising 1-D. We considered the noise to be un-scaled white. The signal was presented by 2048 numerical points. We used soft fixed form of the threshold method. Fig. 9 shows several variants of de-noising of the signal, where the “dmev” wavelet and others were used. All variants give the same result with good accuracy. Thus one can see that the results of the wavelet de-noising allow identifying reliably peaks 1, 2, and 3.

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**Fig. 8** Oscilloscope traces for the cases when direct beam of neutrons (1) was blocked almost completely by a neutron screen (a) and without screening (b)

**Fig. 9** De-noising signals obtained with different wavelet types, level 2, for Fig. 8 (a) and (b)
Same procedure as above has shown that peaks 2 and 3 are belongs to nuclei of phosphorus and oxygen. Taking into account cross-sections and number of atoms in the acid’s molecule we have calculated why both peaks are almost equal by their amplitudes (difference is 1.2 times). Of course, to compare these amplitudes one has to subtract background from the overall signal as it is shown by vertical bars (red lines) in Fig. 9. Thus these set of tests has shown that even $10^8$ neutrons per pulse and TOF base equal about 2 meters can still serve in certain cases in our NINIS technique.

c) Our next experimental session was devoted to lengthy objects. We used our high-pressure cylinder made by aluminium and filled with deuterium at this time up to the pressure of 70 atm. The geometry of the experiment was the same as shown in our MCNP simulations (Fig. 3a). Typical oscilloscope traces are shown in Fig. 10.

![Oscilloscope traces for the case without screen (a) and with a paraffin screen blocking partially X-Rays (1) and direct beam of neutrons (2) but not blocking neutrons scattered by Al (3) and deuterium (4) nuclei](image)

Fig. 10 Oscilloscope traces for the case without screen (a) and with a paraffin screen blocking partially X-Rays (1) and direct beam of neutrons (2) but not blocking neutrons scattered by Al (3) and deuterium (4) nuclei

Difference in time lags between these experimental results and our simulation oscilloscope trace (Fig. 3c) is small. It results from the fact that in our numerical modeling we supposed that DPF irradiates 2.45-MeV neutrons in all directions. In our real situation neutrons irradiated along Z-axis have energy 2.6 MeV. That is why they come to the detector slightly earlier.

It is clearly seen that the pulse of neutrons scattered by deuterium has longer duration compared with the pulse of direct neutrons (its rise-time), which comes from the fact that the length of our object is about 4-5 times longer compared with the thickness of our neutron shell ($\approx 20$ cm). Mean free path (MFP) of neutrons in deuterium at 70 atm is:

$$L_D = 1/n\sigma = 1/2 \times 2 \times 2.7 \times 10^{19} \times 70 \times 2.3 \times 10^{-24} \approx 100 \text{ cm},$$

where $L_D - MFP$, $n$ - nuclei (atoms) concentration in 1 cm$^3$, $2.7 \times 10^{19}$ - Loschmidt’s number, pressure $p=70$ atm, and $\sigma$ - cross-section of elastic scattering, i.e. $L_D$ is about the length of our high-pressure cylinder $l = 1$ m. At the same time the pulse of neutrons scattered by
aluminium wall of the cylinder is short. It reflects the fact that our PMT+S was oriented along the cylinder’s wall, so neutrons scattered by the most distant part of the aluminium wall were absorbed by closer parts of it – MFP in aluminium is 10 cm:

\[ L_{Al} = 1/\nu \sigma = 1/1.7 \times 10^{22} \times 3 \times 10^{-24} \approx 20 \text{ cm}, \]

with \( n = \rho /u \times m_p = 2.7/27 \times 1.67 \times 10^{-24} \), where \( \rho \) – specific density of aluminium, \( u \) – unified atomic mass unity, \( m_p \) – proton’s mass. So MFP here is much less compared with the cylinder length: \( L_{Al} \ll l \). Thus this short single-pulse technique can characterize geometry of objects.

Another issue of the NINIS technology is whether it is possible to use this method for interrogation of really lengthy objects (e.g. sea containers). In this case the most distant point to be irradiated could be at a distance of about 10 meters apart from the DPF chamber. Because distances between the source and the target in the worst case will be larger by 50 times than in the above-described case we must increase neutron yield of the DPF device by 50\(^2\)-times, i.e. by ~ 3 orders of magnitude (up to \( 3 \times 10^{11} \ldots 10^{12} \) n/shot). It can be done by use DPF chamber operating with D-T mixture as a working gas. In this case neutron yield of DPF will be increased by 2 orders of magnitude compared with its operation with pure deuterium [5]. Having the PMT+S system as a monitor we shall know precisely at each moment the configuration of our neutron shell, i.e. we shall know the distance between our scatterers and each particular PMT. It will give us an opportunity for identification of every pulse of scattering neutrons in the manner described above with spatial resolution of about the thickness of our shell 20-50 cm. Use of 2D matrix of the PMTs ensures a characterization of the suspicious object.

d) Use of 14-MeV neutrons was the goal of our next experimental session. Researches were provided with the PF-10 device (ITEP) operating with the chamber filled with the deuterium-tritium mixture as a working gas and with the PF-6 device (IPPLM) now supplied with sealed chambers filled with D-T mixture. In this case of 14-MeV neutrons produced by a DPF chamber we may expect the following features distinguishing this experiment compared with an operation of DPF filled with pure deuterium (producing 2.45-MeV neutrons):

1) Utilization of the 14-MeV neutrons will result in a decrease of the time-of-flight (TOF) of 14-MeV neutrons – and hence in a corresponding lower separation of pulses of elastically scattered 14-MeV neutrons from different elements comprising the substance under interrogation – by a factor of 0.4. It will demand an increase in the corresponding TOF base in this case by the 2.5 times compared with the case of pure deuterium chamber filling (2.45-MeV neutrons), which will in its turn decrease the number of registered scattered
neutrons by a factor 6.25. Cross-sections of elastic scattering of neutrons by nuclei of carbon, nitrogen and oxygen (the elements usually presented in explosives) are less by 1.5-3 times at the energy 14 MeV in comparison with the energy 2.45 MeV. It will also decrease amplitude of our pulses proportionally. However the neutron yield magnitude of a DPF grows in the case of its operation with D-T mixture by one hundred times. So we shall obtain a 5-10-times benefit in the scattering signal gain.

2) Neutron energy equal to 14 MeV is well above a number of thresholds of (n,γ) reactions of neutrons with substances under the interest – oxygen, nitrogen, carbon, hydrogen, etc. Appearance of characteristic gamma rays produced during an inelastic scattering of 14-MeV neutrons (e.g. 8-MeV gamma photons characteristic for nitrogen) may provide additional information, which may be important for the interrogation procedure. These photons generated during such an experiment are either delayed or prompt. Spectrum (characteristic lines of elements) of the first ones can be collected (as it was done e.g. in the paper [6]) by conventional γ-spectrometers whereas the last ones can be recognized by a specialized technique, e.g. by a matrix of PMT tubes equipped with the scintillators in different schemes. Below we describe our initial experiments with 14-MeV neutrons.

At the PF-10 device we provided tests of elastic scattering of neutrons by a 1-litre bottle of nitric acid (HNO₃) with two PMT+S of the type SNFT placed at different distances (see scheme of experiments in Fig. 11). In Fig. 12 we present oscilloscope traces obtained without the target (the bottle of acid).

![Fig. 11 Scheme of experiments provided with DT-mixture as a working gas and a bottle of nitric acid as a target](image)
From analysis of these traces taking into consideration geometrical factors we have deduced the following conclusions about time lags of X-Ray and neutron peaks inside the chamber:

a) 1-st neutron peak appears $\approx 4$ ns after the first X-Ray peak
b) 2-nd (the highest) neutron peak appears at the same moment as the second X-Ray peak
c) 3-rd neutron pulse is generated inside the chamber 40 ns later than the peak of the second X-Ray pulse
d) Velocities of neutrons for the above three neutron pulses look as follows: 1-st pulse – $5.18 \times 10^9$ cm/s, 2-nd – $5.13 \times 10^9$ cm/s, 3-rd – $4.90 \times 10^9$ cm/s
e) Corresponding energies: 1-st pulse – 14.0 MeV, 2-nd – 13.7 MeV, 3-rd – 12.5 MeV.

An important characteristic feature of the discharge here is connected with the second neutron and X-Ray pulses. Usually X-Ray pulse is produced in the DPF chamber by fast electrons generated in the first phase of the acceleration process. Later these fast electrons are magnetized, and the whole current in this second phase are carried by fast ions. Namely these fast ions produce neutrons within the compressed plasma [7]. That is why neutrons (as a consequence of fast ions generation) appear as a rule after an X-Ray pulse – in the same manner as it is in this experiment for the first X-Ray pulse and for the first and third neutron pulses. However the second X-Ray pulse appears here simultaneously with the second (most powerful) neutron pulse. This exception from the above rule seen in all our experiments for these second pulses can be explained by the phenomena of activation of the copper (construction material of the DPF chamber) by 14-MeV neutrons with subsequent irradiation of gamma rays by this material. Besides the coincidence of these two peaks an additional argument in a favor of this explanation is the same duration of both pulses seen in Fig. 3 b for pulses 2 and 5. The increased duration of the pulse 5 in Fig. 3 a is here explained by the pulse spreading due to non-zero width of the neutron spectrum. As we shall see later sometimes the shape of this second neutron pulse when it has long tail gives and evidence of strong scattering of neutrons in surrounding space.
In Fig. 13 we present results of measurements made with the screen placed in front of the DPF chamber but not blocking neutrons scattered by the bottle. The screen was assembled from three layers consisted of the polyethylene/boron bricks of the “Neutronstop” types each. This screen diminished the direct beam of 14-MeV neutrons by approximately 2 orders of magnitude.

**Shot #14** Bottle with HNO₃ “Neutronstop”: 3 layers \( Y_n = 0.49 \cdot 10^{11} \) neutrons/shot

An analysis gave us the following information:

1) Neutrons scattered by the 1-litre bottle with HNO₃ are clearly seen

2) Positions of the neutron pulses in the oscilloscope traces scattered by nitrogen and oxygen nuclei coincide with those calculated for the geometry and distances of our experiment (for PMT+S₁ by 6.0-6.5 ns and for PMT+S₂ by 9.5-10.5 ns later in relation to the peak of direct neutrons correspondingly)

3) The distance from the scatterer to the PMT+S₂ chosen for the experiment (544 cm) is not enough for separation of groups of neutrons scattered by nuclei of nitrogen and of oxygen (about 1 ns) for the neutron pulse duration (approximately 20 ns) generated by our DPF chamber in these two shots. In Fig. 12 one may see the same traces as in Fig. 11 before and after processing of them with the wavelet technique.

At the PF-6 device we have irradiated a high-pressure aluminium cylinder with deuterium at 70 atm by 14-MeV neutrons. However measurements here were provided with
ultra-high temporal resolution by means of MCP-PMT Chevron R3809 U-52 type detector. Typical oscilloscope traces are presented in Fig. 15.

When we use low neutron yield and large distance from the chamber to the detector we may see each individual flash produced by a recoil proton as a result of a single neutron collision (a). The amplitude of the flash depends on the impact parameter. That is why we have different amplitudes of these individual pulses even for adjacent signals. However when we have increased neutron flux these pulses have been merged and averaged (b), and eventually we have an impulse similar to those obtained by conventional technique (c).

In spite of the fact that in the experimental hall we had a very high level of parasitic scattering giving us a long “tail” at the main neutron pulse (3) yet one may clearly see in proper places both pulses of neutrons scattered by aluminium vessel (4) and by deuterium (long pulse 5) as well as first (intrinsic - 1) and second (induced in copper - 2) hard X-Ray pulses – all calculated beforehand.

Now it is interesting to understand how many scattered neutrons can reach and can be captured by our scintillator. Let us make estimations for the most doubtful case of scintillator having 50 cm in diameter and 50 cm by length when DPF irradiate only $10^8$ 2.45-MeV neutrons per pulse. From geometry of the experiment it is easy to calculate that our bottle (10
cm in diameter and 15 cm by height placed at a distance 7.75 cm) encompasses ~1/7 part of the solid angle thus giving a figure for total number of neutrons irradiated it equal to about 14%. The above-mentioned cross-sections give evidence that the majority of neutrons coming to the bottle will be scattered by it. It means that the total number of scattered neutrons will be: $10^8 \times 0.17 \approx 1.7 \times 10^7$. At the distance of 2.2 meters where we have our S+PMT-1 the neutron flux density will be equal to 25 n/cm². Taking into consideration that the neutron-receiving surface of the scintillator is $2 \times 10^3$ cm² and that almost a half of our neutrons ($E_n \sim$ 2.5 MeV) will be captured by the scintillator of this thickness we obtain for the number of neutrons forming two our pulses (scattered by O and N nuclei) the figure more than $10^5$ neutrons (note that nuclei of hydrogen do not scatter neutrons in this our geometry). This is a reasonable body for the two pulses of acceptable quality (i.e. we obtain rather good statistics).

We have to mention here that one may see several additional peaks on the oscilloscope traces having nothing with our object under interrogation. They results from the neutron elastic scattering due to various elements of our DPF device such as DPF chamber (Cu), current collector (Cu), 4 transformers, 4 capacitors filled with castor oil, polyethylene and Teflon plates, cables, etc. They are positioned on different distances from the neutron source (usually further compared with the position of our bottle) and at dissimilar angles. However we know where we have to expect the peaks of our interest in the oscilloscope traces (usually first pulses of the chain) beforehand, and we found them namely in these time positions. Fortunately in this case we have no overlapping of these peaks with peaks from other elements as it was proved by the amplitude analysis.

The method proposed has of course some restrictions. As it was shown in many works all explosive substances have in their contents hydrogen (a.w. = 1), carbon (a.w. = 12), nitrogen (a.w. = 14), oxygen (a.w. = 16) (and sometimes potassium (a.w. = 39). At the same time the main feature, which differs explosives from another substances, is the almost equal percentage of the above 4 main elements (H, C, O, and N) within them in contrast to common materials (see e.g. [1]). It means that taking into account cross-sections of elastic scattering of neutrons by the above nuclei we can expect the predictable (almost equal) amplitudes of the three peaks of neutrons scattered backward from C, O, N and separated one from another by the predictable time-delays as well as one peak of about the same amplitude scattered forward from H nuclei (at a proper choice of the scattering angles). Namely presence of these 4 peaks at two PMT’ oscilloscope traces will be a “signature” of an explosive in a box under interrogation.
Of course it is possible that some other element positioned at another distance (and/or at another angle) may give a scattering peak, which overlap one of our peaks. In these circumstances still we shall have 3 suspicious peaks yet of distorted amplitudes. This is one of the restrictions of the method. However in this case we may repeat our shot making it at a different angle (rotating the object under interrogation). After this procedure we shall distinguish our peaks. Or we may use 3 PMT+S placing the 3rd one at a different angle. Then we may compare our suspicious peaks in the same shot.

**Perspectives**

We believe that the perspectives of this method lie in use of both 2.45- and 14-MeV neutrons simultaneously (i.e. in filling of DPF by DT-mixture as a working gas) with measurements of elastically scattered neutrons of both energies, in measurements of characteristic photons appeared due to \((n,\gamma)\) inelastic neutron scattering, in application of hard X-Ray imaging of an object during the same DPF shot, and in elaboration of automated (computer-aided) procedure of the identification of chemical content of details (sub-items) of an object using X-Ray image in combination with data obtained from elastically and inelastically scattered neutrons in a single DPF shot.

**Literature**

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